HIGHLIGHTS and CONCLUSIONS

of the Chalonge CIAS Meudon Workshop 2010:

'Dark Matter in the Universe and Universal Properties of Galaxies: Theory and Observations',

Ecole Internationale d'Astrophysique Daniel Chalonge Meudon campus of Observatoire de Paris in the historic Château, 8-11 June 2010.

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FIG. 1: Poster of the Workshop

FIG. 2: Photo of the Group

I. PURPOSE OF THE WORKSHOP AND INTRODUCTION

The Workshop addressed the problem of Dark Matter in the Universe and the Universal properties of Galaxies, with an effort of clarification and synthesis by combining in a conceptual framework, theory, analytical, observational and numerical simulation results.

The subject have been approached in a threefold way:

(I) Conceptual context: Dark Matter in cosmology and astrophysics: current status, perspective and prospective of the research in the subject: theory and observations.

(II) Astronomical observations linked to the galaxy structural properties and especially to the universal properties of galaxies: high quality rotation curves, kinematics, density profiles, gravitational lensing, small and large structures.

(III) Numerical simulations, large structures, structures and substructures.

Topics addressed by the Workshop included: Kinetic theory and the recent progress in solving the Boltzmann-Vlasov equation to obtain the observed universal properties of galaxies. The dark matter surface density in galaxies. The phase-space density of dark matter. Observations of Galaxy properties, surface density and universal profiles Discrepancies between numerical simulations results and observations. Particle model independent analysis of astrophysical dark matter. The mass of the dark matter particle at the keV scale from theory combined to observations and numerical simulations. The impact of the mass of the dark matter particle on the small scale structure formation and the choice of the initial conditions. The radial profiles and the Dark Matter distribution. Cores vs. Cusps. The recently highlighted keV scale Dark Matter.

Sessions lasted for four full days in the beautiful Meudon campus of Observatoire de Paris, where CIAS 'Centre International d'Ateliers Scientifiques' is located. All sessions took place in the historic Meudon Château, (built in 1706 by great architect Jules-Hardouin Mansart in orders by King Louis XIV for his son the Grand Dauphin).

The Meeting was open to all scientists interested in the subject. All sessions were plenary followed by discussions. The format of the Meeting was intended to allow easy and fruitful mutual contact and communication with large time devoted to discussions. All Informations about the meeting, are displayed at

http://www.chalonge.obspm.fr/Cias_Meudon2010.html

The presentations by the lecturers are available on line (in .pdf format) in 'Programme and Lecturers' in the above link, as well as the photos of the Workshop. We thank all again, both lecturers and participants, for having contributed

so much to the great success of this Workshop and look forward to seeing you again in the next Workshop of this series.

We thank the Observatoire de Paris and the CIAS support, as well as the logistics assistance, the secretariat and all those who contributed so efficiently to the successful organization of this Workshop.

With compliments and kind regards,

Hector J de Vega, Norma G Sanchez

II. PROGRAMME AND LECTURERS

- **Peter BIERMANN** (MPI-Bonn, Germany & Univ of Alabama, Tuscaloosa, USA) Astrophysical Dark Matter, keV scale particle and fermion condensates.
- **Alfonso CAVALIERE** (Dipt Fisica/Astrofisica, Unuv Roma 2 Tor Vergata, Italy) The Intra Cluster Medium in Dark Matter Halos
- **Hector J. DE VEGA** (CNRS LPTHE Univ de Paris VI, France) Galaxy properties from linear primordial fluctuations and keV scale dark matter from theory and observations
- **Gianfranco GENTILE** (Math Physics & Astronomy, Univ of Ghent, Ghent, Belgium) S urface densities and dark matter properties in galaxies
- **Yehuda HOFFMAN** (Racah Inst of Physics, Hebrew Univ, Jerusalem, Israel) Dark matter halos with and without baryons
- **Chanda J. JOG**, Department of Physics, Indian Institute of Science, Bangalore, IndiaDetermination of the density profile of the dark matter halos in galaxies
- **Anatoly KLYPIN** (Dept. of Astronomy, New Mexico State University, USA) Stefan GOTTLOBER(Astr Inst Postdam, Postdam, Germany) Dark matter halos from N-body simulations. Bolshoi N-body Cosmological Simulation
- **Andrea LAPI** (Dipt Fisica/Astrofisica, Univ Roma 2 Tor Vergata, Rome, Italy) Probing Dark Matter Halos in Galaxies and their Clusters
- **Jounghun LEE** (Dep. Phys. & Astronomy, Seoul National University, Seoul, South Korea) Bullet Clusters and its Cosmological Implications
- **Andrea V. MACCIO** (Max Planck Institut fur Astronomie, Heidelberg, Germany) Dark Matter at small scales: the lesson from Milky Way satellites
- **Paolo SALUCCI** (SISSA-Astrophysics, Trieste, Italy) Universality Properties in Galaxies and Cored density Profiles
- **Norma G. SANCHEZ** (CNRS LERMA Observatoire de Paris, Paris, France) Galaxy properties, keV scale dark matter from theory and observations and the power of linear approximation
- **Pasquale D. SERPICO** (CERN-Theory Division & LAPTH Annecy-le-Vieux, France) Astrophysical explanations of the cosmic positron excess in Pamela and Fermi
- **Rainer STIELE** (Inst Theor Phys, Heidelberg University, Heidelberg, Germany) Cosmological bounds on dark matter self-interactions
- **Janine VAN EYMEREN** (Univ of Manchester UK & Duisburg-Essen, Germany) Non-circular motions and the Cusp/Core discrepancy in dwarf galaxies
- **Matthew G. WALKER** (Institute of Astronomy, University of Cambridge, UK) A universal mass profile for dwarf spheroidal galaxies.
- **Markus WEBER** (Inst fur Experimentelle Kemphysik, Karlsruher Inst. fur Technologie KIT, Karlsruhe, Germany) The determination of the local Dark Matter density
- **Gustavo YEPES** (Grupo de Astrofisica, Univ Autonoma de Madrid, Cantoblanco, Spain) How warm can dark matter be ?. Constraining the mass of dark matter particles from the Local Universe
- **Gabrijela ZAHARIJAS**, (IphT/CEA-Saclay, Gif-sur-Yvette, France) Dark matter constraints from the Fermi-LAT observations

III. HIGHLIGHTS BY THE LECTURERS

A. Peter Biermann[1,2,3,4,5]

with help from Julia K. Becker[6], Laurentiu Caramete[1,7], Lou Clavelli[3], Jens Dryer[6], Ben Harms[3], Athina Meli[8], Eun-Suk Seo[9], & Todor Stanev[10]

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The nature of dark matter

Dark matter has been detected since 1933 (Zwicky) and basically behaves like a non-EM-interacting gravitational gas of particles. From particle physics Supersymmetry suggests with an elegant argument that there should be a lightest supersymmetric particle, which is a dark matter candidate, possibly visible via decay in odd properties of energetic particles and photons:

We have discovered i) an upturn in the CR-positron fraction, ii) an upturn in the CR-electron spectrum, iii) a flat radio emission component near the Galactic Center (WMAP haze), iv) a corresponding IC component in gamma rays (Fermi haze), v) the 511 keV annihilation line also near the Galactic Center, and most recently, vi) an upturn in the CR-spectra of all elements from Helium.

All these features can be quantitatively explained with the action of cosmic rays accelerated in the magnetic winds of very massive stars, when they explode (Biermann et al. 2009, 2010), based on predictions from 1993 (Biermann 1993, Biermann & Cassinelli 1993, Biermann & Strom 1993, Stanev et al 1993). This allows to go back to galaxy data to derive the key properties of the dark matter particle: Work by Hogan & Dalcanton (2000), Gilmore et al. (from 2006, 2009), Strigari et al. (2008), and Boyanovsky et al. (2008) clearly points to a keV Fermion particle.

A right-handed sterile neutrino is a candidate to be this particle (e.g. Kusenko & Segre 1997; Fuller et al. 2003; Kusenko 2004; for a review see Kusenko 2009; Biermann & Kusenko 2006; Stasielak et al. 2007; Loewenstein et al. 2009):

This particle has the advantage to allow star formation very early, near redshift 80, and so also allows the formation of supermassive black holes, possibly formed out of agglomerating massive stars.

Black holes in turn also merge, but in this manner start their mergers at masses of a few million solar masses. This readily explains the supermassive black hole mass function. The corresponding gravitational waves are not constrained by any existing limit, and could have given a substantial energy contribution at high redshift.

Our conclusion is that a right-handed sterile neutrino of a mass of a few keV is the most interesting candidate to constitute dark matter.

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The Intra Cluster Medium in Dark Matter Halos

In galaxy clusters the gravitational potential wells set by dark matter (DM) masses $M \sim 10^{15}\, M_\odot$ are filled out to the virial radius $R \sim$ Mpc by a hot thin medium at temperatures $k_B T \sim$ several keVs, with central particle densities $n \sim 10^{-3}$ cm^{-3}.

Such a medium constitutes a remarkably good electron-proton plasma (appropriately named IntraCluster Plasma, ICP), with a huge ratio of thermal to mean electrostatic energy $k_B T/e^2\, n^{1/3} \sim 10^{12}$. It emits copious X-ray powers $L_X \propto n^2\, T^{1/2}\, R^3 \sim 10^{45}$ erg s^{-1} via thermal bremsstrahlung; but over most of the cluster volume the large thermal energy content $E \propto n\, k_B T\, R^3 \approx 10^{63-64}$ ergs makes the radiative cooling time longer than the cluster age.

From the macroscopic viewpoint, the ICP constitutes a simple fluid with 3 degrees of freedom and effective particle mass $\mu m_p \approx 0.6\, m_p$ in terms of the proton's m_p. So it grants precision modeling as for the space distributions of density $n(r)$ and temperature $T(r)$, such as to match the rich amount of current data concerning the emissions in X rays, and the upcoming measurements of the Sunyaev-Zel'dovich scattering in μwaves.

Handy and effective modeling is provided by the Supermodel. This is based on the run of the ICP 'entropy' (adiabat) $k \equiv k_B T/n^{2/3}$ provided the physical processes for its production. The entropy is raised both at the cluster centers due to the energy discharged by deep mergers and AGN outbursts, and at the virial boundary from shocking the gravitational inflow of external gas accreted along with the DM. These processes together originate ICP entropy profiles with shapes $k(r) = k_c + (k_R - k_c)\,(r/R)^a$ comprising a central floor $k_c \approx 10 - 100$ keV cm^2, and an outer ramp with slope $a \approx 1.1$ adjoining to the boundary values $k_R \sim$ a few 10^3 keV cm^2, consistent with the recent analyses of wide cluster samples in X rays.

The ensuing gradient of the thermal pressure $p(r) \propto k(r)\, n^{5/3}(r)$ is used in the Supermodel to balance the DM gravitational pull $-G\, M(< r)/r^2$, and sustain hydrostatic equilibrium. The latter is solved to *directly* yield the temperature profile in terms of the entropy run $k(r)$. Density and temperature are *linked* together by $n(r) = [k_B T(r)/k(r)]^{3/2}$, so the related X-ray observables are readily derived and compared with data. With the three specific parameters appearing in $k(r)$ the Supermodel has provided remarkably good fits to the X-ray data on surface brightness and temperature profiles for several galaxy clusters. The fits not only include the central morphologies from cool-core to non-cool-core (CCs and NCCs), but also cover diverse outer behaviors including the steep temperature profiles recently observed. The Supermodel also enables us to derive from X rays the the DM concentration c; this yields the cluster Grand Design illustrated in Fig. 1. The interested reader may himself try more clusters on using the fast Supermodel algorithm made available at the website *http://people.sissa.it/~lapi/Supermodel/*.

Currently we are working toward including the additional support to ICP equilibrium provided by turbulence; this is driven by inflows of intergalactic gas across the cluster boundary and past the accretion shocks. We find (consistently with X-ray observations) that such phenomena are increasingly important at low redshifts, when the shocks weaken and the infall itself subside due to the accelerating Universe and the feeding on the initial perturbation wings.

Thus the Supermodel is proving to be an interesting and handy tool to model and probe turbulence amplitude and decay scale in a plasma. This constitutes an enticing if complex astrophysical issue, such to warrant close *modeling* and *probing*.

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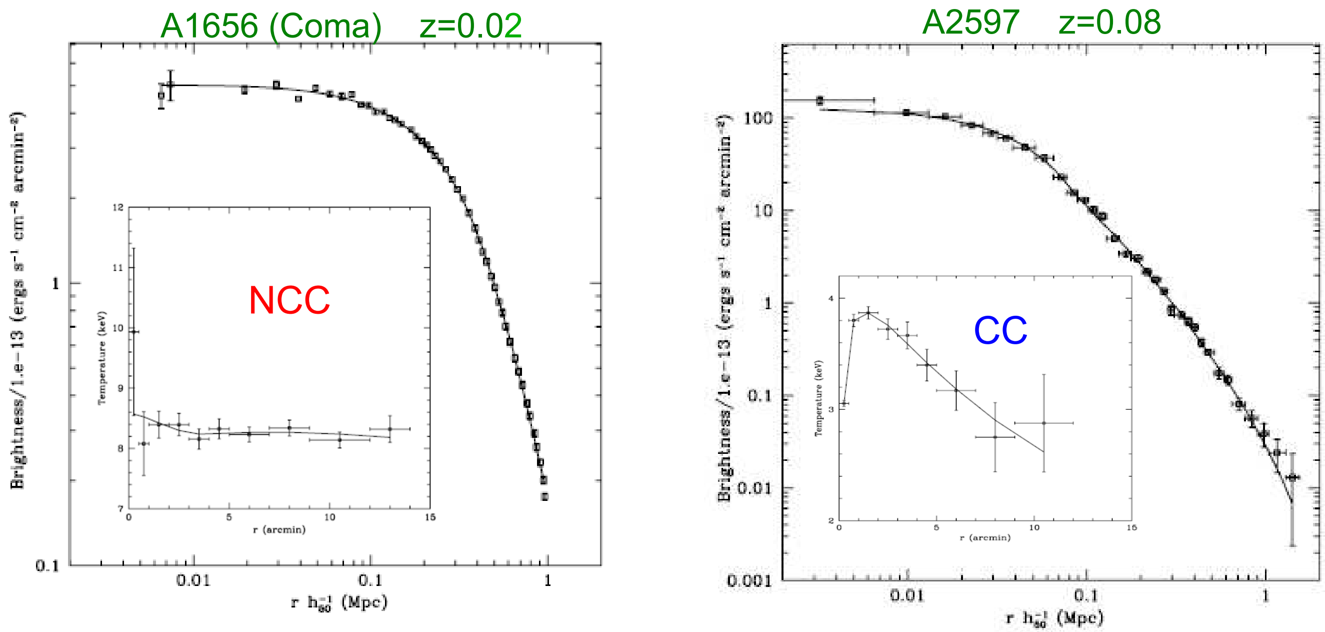

FIG. 3: The cluster Grand Design resulting from development of the DM halos and ICP analyses with the Supermodel, is illustrated with examples of X-ray brightness profiles (projected temperatures in the insets). Outer production modulates the outskirts, while central entropy marks the CC/NCC dichotomy, which we find correlated to high/low DM concentrations.

C. Hector J. de Vega

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Galaxy properties from linear primordial fluctuations and keV scale dark matter from theory and observations

The Standard ΛCDM Cosmological Model begins by the **inflationary** era, slow-roll inflation explains the horizon and flatness features of the present Universe and gravity is described by Einstein's General Relativity. Particle Physics is described by the Standard Model of particle physics: the $SU(3) \otimes SU(2) \otimes U(1) =$ (qcd+electroweak model). Dark matter must be **cold** (non-relativistic) when structure formation happens. DM is outside the SM of particle physics. Finally, the dark energy is described by the cosmological constant Λ. The standard Cosmological model has been validated by a huge host of data of completely different nature obtained by independent methods from many kinds of astrophysical and cosmological observations.

In the context of the standard Cosmological model the nature of DM is unknown. However, it is a forefront problem of modern cosmology since 83% of the matter in the universe is dark. Only the DM gravitational effects are noticed and they are necessary to explain the present structure of the Universe.

DM (dark matter) particles must be neutral and so weakly interacting that no effects are so far detectable. Extremely many candidates in particle physics models beyond the standard model of particle physics.

Theoretical analysis combined with astrophysical data from galaxy observations points towards a DM particle mass in the **keV scale** (keV = 1/511 electron mass) [1-4].

DM particles can decouple being ultrarelativistic (UR) at $T_d \gg m$ or non-relativistic $T_d \ll m$. They may decouple at or out of local thermal equilibrium (LTE).

The DM distribution function: $F_d[p_c]$ freezes out at decoupling becoming a function of the comoving momentum $p_c =$. $P_f(t) = p_c/a(t) =$ is the physical momentum.

Basic physical quantities can be expressed in terms of the distribution function as the velocity fluctuations,

$$\langle \vec{V}^2(t) \rangle = \langle \frac{\vec{P}_f^2(t)}{m^2} \rangle = \left[\frac{T_d}{m\, a(t)} \right]^2 \frac{\int_0^\infty y^4 F_d(y) dy}{\int_0^\infty y^2 F_d(y) dy} \tag{3.1}$$

and the DM energy density,

$$\rho_{DM}(t) = \frac{m\ g}{2\pi^2} \frac{T_d^3}{a^3(t)} \int_0^\infty y^2\ F_d(y)\ dy \ , \tag{3.2}$$

where $y = P_f(t)/T_d(t) = p_c/T_d$ is the integration variable and g is the number of internal degrees of freedom of the DM particle; typically $1 \leq g \leq 4$.

Two basic quantities characterize DM: its particle mass m and the temperature T_d at which DM decouples. This last quantity is related by entropy conservation to the number of ultrarelativistic degrees of freedom g_d at decoupling by $T_d = \left(\frac{2}{g_d}\right)^{\frac{1}{3}}\ T_{cmb}\ ,\ T_{cmb} = 0.2348\ 10^{-3}$ eV. Notice that $F_d(y)$ is of order one and that eqs.(3.1) and (3.2) are valid all the time before structure formation.

One therefore needs **two** constraints to determine the values of m and T_d (or g_d).

One constraint is to reproduce the known cosmological DM density today. $\rho_{DM}(\text{today}) = 1.107\ \frac{\text{keV}}{\text{cm}^3}$.

Two independent further constraints are considered in refs. [1-4]. First, the phase-space density $Q = \rho/\sigma^3$ [1-2] and second the surface acceleration of gravity in DM dominated galaxies [3-4]. We therefore provide **two** quantitative ways to derive the value m and g_d in refs. [1-4].

The phase-space density Q is invariant under the cosmological expansion and can **only decrease** under self-gravity interactions (gravitational clustering). The value of Q today follows observing dwarf spheroidal satellite galaxies of the Milky Way (dSphs): $Q_{today} = (0.18 \text{ keV})^4$ (Gilmore et al. 07 and 08). We compute explicitly Q_{prim} (in the primordial universe) and it turns to be proportional to m^4 [1-4].

During structure formation ($z \lesssim 30$), Q **decreases** by a factor that we call Z. Namely, $Q_{today} = Q_{prim}/Z$. The value of Z is galaxy-dependent. The spherical model gives $Z \simeq 41000$ and N-body simulations indicate: $10000 > Z > 1$ (see [1]).

Combining the value of Q_{today} and ρ_{DM}(today) with the theoretical analysis yields that m must be in the keV scale and T_d can be larger than 100 GeV. More explicitly, we get from eqs.(3.1) and (3.2) general formulas for m and g_d:

$$m = \frac{2^{\frac{1}{4}}\ \sqrt{\pi}}{3^{\frac{3}{8}}\ g^{\frac{1}{4}}}\ Q_{prim}^{\frac{1}{4}}\ I_4^{\frac{3}{8}}\ I_2^{-\frac{5}{8}}\ , \quad g_d = \frac{2^{\frac{1}{4}}\ g^{\frac{3}{4}}}{3^{\frac{3}{8}}\ \pi^{\frac{3}{2}}\ \Omega_{DM}}\ \frac{T_\gamma^3}{\rho_c}\ Q_{prim}^{\frac{1}{4}}\ [I_2\ I_4]^{\frac{3}{8}}$$

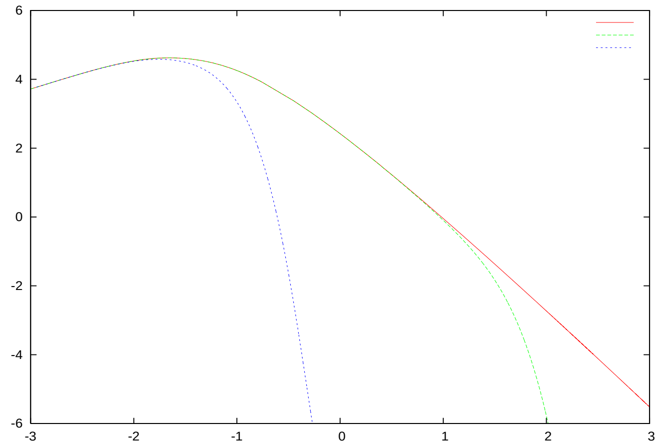

FIG. 4:

where $I_{2\,n} = \int_0^\infty y^{2\,n} \;\; F_d(y) \;\; dy$, $n = 1, 2$ and $Q_{prim}^{\frac14} = Z^{\frac14}$ 0.18 keV using the dSphs data, $T_\gamma = 0.2348$ meV , $\Omega_{DM} = 0.228$ and $\rho_c = (2.518 \text{ meV})^4$.

These formulas yield for relics decoupling UR at LTE:

$$m = \left(\frac{Z}{g}\right)^{\frac14} \text{ keV} \begin{cases} 0.568 \\ 0.484 \end{cases} , \; g_d = g^{\frac34} \; Z^{\frac14} \begin{cases} 155 & \text{Fermions} \\ 180 & \text{Bosons} \end{cases} .$$

Since $g = 1-4$, we see that $g_d \gtrsim 100 \Rightarrow T_d \gtrsim 100$ GeV. Moreover, $1 < Z^{\frac14} < 10$ for $1 < Z < 10000$. For example for DM Majorana fermions ($g = 2$) $m \simeq 0.85$ keV.

Results for m and g_d on the same scales for DM particles decoupling UR out of thermal equilibrium [1].

For a specific model of sterile neutrinos where decoupling is out of thermal equilibrium:

$$0.56 \text{ keV} \lesssim m_\nu \; Z^{-\frac14} \lesssim 1.0 \text{ keV} \quad , \quad 15 \lesssim g_d \; Z^{-\frac14} \lesssim 84$$

So far we considered UR decoupling. For relics decoupling non-relativistic we obtain similar results for the DM particle mass: keV $\lesssim m \lesssim$ MeV [1].

The value of the DM particle mass affects the linear primordial power today for small scales. We plot in fig. 4 $\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for WIMPS (red), 1 keV DM particles (green) and 10 eV DM particles (blue). Recall that $P(k) = P_0 \; k^{n_s} \; T^2(k)$ where $T(k)$ is the transfer function in the MD era that we computed from the Gilbert integral equation [5]. The power $P(k)$ turns to be cutted for 1 keV DM particles on scales $\lesssim 100$ kpc. For scales **larger** than ~ 100 kpc, DM particles and wimps give **identical** results. 10 eV DM particles are ruled out because they suppress all structures below ~ 3 Mpc.

Many extensions of the SM of particle physics include a DM particle with mass in the **keV scale** and weakly enough coupled to the SM particles to fulfill all particle physics experimental constraints. Main candidates in the keV mass scale: sterile neutrinos, light gravitinos, light neutralino, majoron ...

The proposal of sterile neutrinos is motivated by the fact that there are both left and right handed quarks. It is then natural to have right handed neutrinos ν_R besides the known left-handed neutrino (quark-lepton similarity).

Sterile neutrinos can transmute into ordinary neutrinos and viceversa through mixing (non-diagonal mass terms). For $m_{\text{sterile}\nu} \sim 1$ keV and $m_{\text{ordinary }\nu} \sim 0.1$ eV the mixing angle turns to be $\theta \sim 10^{-4}$. This small value is appropriate to produce enough sterile neutrinos to account for the observed DM. Smallness of θ makes very difficult to detect steriles. The most promising experiments are those of beta decay where a sterile should be produced instead of an ordinary neutrino with probability $\sim \theta^2$. In particular, renium and tritium beta decay are the best candidates since they provide the lowest energy yield.

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Surface densities and dark matter properties in galaxies

Rotation curves of spiral galaxies (their rotation velocity as a function of galactocentric radius) do not decline as expected from the observed distribution of matter. Two proprosed solutions are either to envisage that galaxies are embedded in a halo of yet-to-be-discovered particles (a dark matter halo), or to consider the possibility (e.g. MOND, Modified Newtonian Dynamics, Milgrom 1983) that gravity does not behave exactly as we would expect from the extrapolation to very weak fields of the known Newton (or Einstein) gravities.

The current standard framework of formation of structures in the Universe is the so-called Λ Cold Dark Matter (ΛCDM) framework. Standard (dark matter only) ΛCDM simulations of structure formation in the Universe result in dark matter halos characterised by a central density "cusp" ($\rho \propto r^{-1}$ for small radii; the exact value of the asymptotic inner slope is still a matter of debate), whereas the observations (e.g. Gentile et al. 2005, 2007; van Eymeren et al. 2009; de Blok 2010, and references therein) tend to favour central constant density cores. Systematic effects that would invalid this conclusion (e.g., non-circular motions, resolution effects) seem to be under control, thanks to improved observational and analysis techniques. From the theoretical point of view, the effect of baryons on dark matter structures is not trivial to implement. The best understood effect of baryons is adiabatic contraction (e.g., Blumenthal et al. 1986, Sellwood & McGaugh 2005), where the dark matter halo however becomes even more centrally concentrated (and therefore even more in contrast with observations) as a result of baryons cooling and infall in the central parts of the dark matter halo. On the other hand, some groups (e.g. Mashchenko et al. 2008, Governato et al. 2010) have produced simulations where approximately constant density cores are formed, as a result of feedback processes linked to star formation. However, consensus is far from being reached on how to implement baryonic physics in dark matter simulations.

One of the most widely used functional forms for a cored halo is the so-called Burkert halo (Burkert 1995):

$$\rho_{\rm Bur}(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)}, \tag{3.3}$$

where ρ_0 is the central density and r_0 is the core radius.

Donato et al. (2009) analysed a sample of galaxies (with published mass models) of all Hubble types and spanning 14 galaxy magnitudes. They reached the conclusion (already noted by Kormendy & Freeman 2004 and Spano et al. 2008 for smaller samples and with fewer galaxy types) that the product $\rho_0 r_0$ is approximately the same for all galaxies: $\rho_0 r_0$=141^{+82}_{-52} M$_\odot$ pc^{-2}. This is equivalent to the average dark matter surface density within r_0: $<\Sigma>_{0,DM} = M(<r_0)/(\pi r_0^2) \sim 0.51 \rho_0 r_0 = 72^{+42}_{-27}$ M$_\odot$ pc^{-2}, which is also equivalent to the gravitational acceleration generated by dark matter at r_0: $g_{DM}(r_0) = G\pi <\Sigma>_{0,DM} = 3.2^{+1.8}_{-1.2}\, 10^{-9}$cm s^{-2}.

In Gentile et al. (2009) we found that also the *baryonic* surface density within r_0 is universal, see Fig. 1. When expressed in terms of the gravitational acceleration generated by baryons at r_0, this universality reads: $g_b(r_0) = 5.7^{+3.8}_{-2.8}\, 10^{-10}$ cm s^{-2}.

We note that these universal relations hold at r_0, even though within the galaxies of our sample the *central* surface density of baryons varies by more than four orders of magnitude (Donato et al. 2009).

The interpretation of these universal relations is far from being simple. However, these relations seem to point to the idea that dark matter "knows" what baryons are doing: at r_0, the gravitational acceleration due to dark matter and the gravitational acceleration due to baryons are about the same for every galaxy. From the gravitational field of baryons, one can derive (roughly) dark matter properties.

If the dark matter particle has a mass around 1-2 keV, then de Vega, Salucci & Sanchez (2010) have shown that it can reproduce the observed universality of dark matter surface density.

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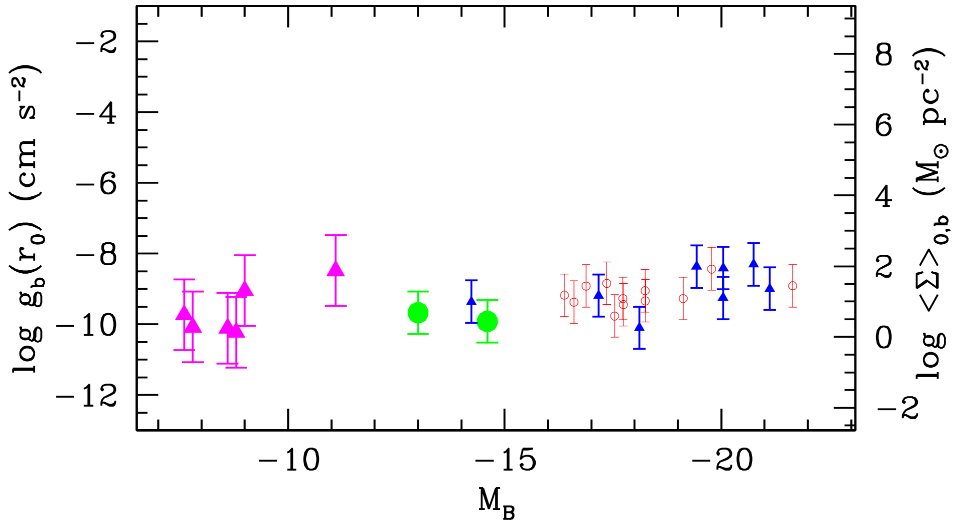

FIG. 5: Universality of the average surface density (and gravity) of baryons within the halo core radius (plotted against B-band absolute magnitude; from Gentile et al. 2009). Different symbols indicate different galaxy subsamples.

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Tracing the dark matter halos of galaxies by modeling the observed HI data

Abstract

We use the observed rotation curves and the HI vertical scaleheight data as simultaneous constraints to obtain the density profile and the shape of the dark matter halos in galaxies, and show these to be varied. A galaxy is modeled as a gravitationally coupled star-gas system in the field of the dark matter halo. This approach is applied to three galaxies: the Milky Way, M31 and UGC 7321, a low surface brightness galaxy. The resulting dark matter profile is not universal.

Introduction

In a typical spiral galaxy like our Galaxy, stars constitute $\sim 90\%$ of the visible mass while the rest is in the interstellar gas. Due to its lower dispersion, gas is important for the disk dynamics despite its lower mass content. Further, the interstellar atomic hydrogen gas (HI) extends 2-3 times farther out than the stellar disk, hence it is an excellent tracer of dynamics in the outer regions of a galaxy.

The observed rotation curve has been routinely used in the literature to study the radial mass distribution within a galaxy, and it is well-known that the dark matter progressively dominates in the outer parts. However, the shape of the dark matter halo is not well-studied. We use the observed vertical thickness of the HI gas distribution as an additional, complementary constraint to model the vertical density distribution and hence the shape of the halo.

Calculations and Results

A galactic disk is supported vertically by pressure, and the balance of self-gravity and pressure decides its thickness. This was studied for a one-component, gravitating isothermal disk in a classic paper by Spitzer (1942). However, a real galaxy consists of stars and gas, where the gas gravity could play a crucial role in determining the vertical distribution since the gas lies closer to the mid-plane. To study this, we have developed a model where stars and gas are taken to be gravitationally coupled, and are embedded in the field of a rigid dark matter halo (Narayan & Jog 2002).

We solve the equations of hydrostatic equilibrium along z for stars and gas and the joint Poisson equation together to obtain a self-consistent solution for the vertical disk density distribution. The coupled, second-order differential equations are solved numerically and iteratively. A general four-parameter dark-matter halo profile as motivated from the dynamical studies of elliptical galaxies (de Zeeuw & Pfenniger 1988) is used where the four parameters are: ρ_0, the central density; R_c, the core radius; q, the vertical to planar axis ratio; and p, the power-law density index. The grid of halo parameters is scanned systematically. For different trial halo parameters, we obtain the rotation curve and the vertical scaleheights at different radii using our model. We then compare these with the observations to get the best-fit halo parameters. This approach has been applied to study three galaxies and the results are summarized in Table 1.

For the nearby Andromeda galaxy, our best-fit model gives an isothermal, flattened halo with an axis ratio of 0.4 (Banerjee & Jog 2008). This lies at the most oblate end of the distribution obtained from cosmological simulations. For the low surface brightness, superthin galaxy UGC 7321, we find that the best-fit halo-core radius is comparable to the stellar disk scalelength. Thus the dark matter halo dominates the dynamics even at small radii in a LSB galaxy (Banerjee, Matthews & Jog 2010). For the Galaxy, the best-fit to the HI data indicates a spherical halo with a density falling faster than for an isothermal case (Narayan, Saha & Jog 2005). Thus, the dark matter halo profile in spiral galaxies does not appear to be universal.

The three crucial parameters that determine the disk vertical HI distribution are the disk-to-halo mass ratio, the gas velocity dispersion, and the shape of the halo. Our work underlines the potential of this approach for further systematic study of the dark matter halo parameters in different galaxy types. For this we need data for outer-galactic HI scaleheights & gas dispersion - this remains a challenging task as was already pointed out by Sancisi & Allen (1979) in their study of NGC 891.

The shape of the dark matter halo in the disk plane is also an important parameter in the study of galaxy formation and evolution. However, this has not been studied much so far. Recent, detailed Leiden/Argentine/Bonn HI survey of the Milky Way Galaxy shows the gas thickness to be azimuthally asymmetric with the flaring being much higher in the North. We assume the gas to be in a hydrostatic equilibrium, and model the above asymmetry of thickness

TABLE I: **Density profile and shape of best-fit dark matter halo**

Name of galaxy	Radial profile	shape, q = vertical to planar axis ratio
M 31	$1/R^2$	oblate, q=0.4
UGC 7321	$1/R^2$	spherical, q=1.0
The Galaxy	$1/R^4$	spherical, q=1.0

to constrain the shape of the halo in the disk plane. We conclude that the Galactic dark matter halo is lopsided and elongated in the disk plane (Saha et al. 2009).

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Universal Properties in Galaxies and Cored DM Profiles.

The presence of large amounts of unseen matter in galaxies, distributed differently from stars and gas, is well established from rotation curves which do not show the expected Keplerian fall-off at large radii, but remain increasing, flat or start to gently decrease over their observed range. The invisible mass component becomes progressively more abundant at outer radii and for the less luminous galaxies (Persic and Salucci and Stel 1996).

In Spirals we have the best opportunity to study the global mass distribution: the gravitational potentials of a spherical stellar bulge, a dark halo, a stellar disk and a gaseous disc give rise to an observed equilibrium circular velocity $V^2(r) = r\frac{d}{dr}\phi_{tot} = V_b^2 + V_{DM}^2 + V_*^2 + V_{HI}^2$. The Poisson equation relates the surface (spatial) densities of these components to the corresponding gravitational potentials. The investigation is not difficult: e.g. $\Sigma_*(r)$, the surface stellar density is proportional (by the mass-to-light ratio) to the observed surface brightness: $\Sigma_*(r) = \frac{M_D}{2\pi R_D^2}\, e^{-r/R_D}$ and then $V_*^2(r) = \frac{GM_D}{2R_D} x^2 B\left(\frac{x}{2}\right)$, where M_D is the disk mass and R_D is the disk scale length.

First, there exists, at any galactocentric radii measured in terms of disk length-scale $R_n \equiv (n/5)R_{opt}$, a *radial* Tully-Fisher relation (Yegorova and Salucci 2007) between the local rotation velocity $V_n \equiv V_{rot}(R_n)$ and the total galaxy luminosity $M_{band} = a_n \log V_n + b_n$. These relationships have a so very low scatter that imply that Dark and Luminous matter are coupled.

PSS and by Salucci et al 2007 *et al.* have evidenced that these systems present Universal features in their kinematics well correlating with the global galactic properties. This has led to the construction, from 3200 individual RCs, of the "Universal Rotation Curve" of Spirals $V_{URC}(r; P)$ (see PSS), i.e. an empirical function of galactocentric radius r, that, tuned by a global galaxy property (e.g. the luminosity), can well reproduce the RC of any object. Additional kinematical data and virial velocities $V_{vir} \equiv (GM_{vir}/R_{vir})^{1/2}$, obtained by Shankar *et al.* 2006, have determined the URC out to the virial radii (Salucci *et al.* 2007).

V_{URC} is the observational counterpart of the velocity profile that emerges out of numerical cosmological simulations. As individual RCs, it implies a mass model including a Freeman disk and a DM halo with a Burkert profile $\rho(r) = \frac{\rho_0\, r_0^3}{(r+r_0)\,(r^2+r_0^2)}$. r_0 is the core radius and ρ_0 the central density, see Salucci and Burkert 2000 for details.

To assume a cored halo profile is obligatory. It is well known that ΛCDM scenario provides a successful picture of the cosmological structure formation and that large N-body numerical simulations performed in this scenario lead to the commonly used NFW halo cuspy spatial density profile. However, a careful analysis of about 100 high quality, extended and free from deviations from axial symmetry RCs has now strongly disfavored the disk + NFW halo mass model, in favor of cored profiles, (e.g. Gentile *et al.* 2004, 2005, Spano *et al.* 2007, de Blok 2008 and de Naray *et al.* 2008).

The structural parameters ρ_0, r_0, M_D are obtained for the URC and for any individual RC by χ^2 fitting. As result, a cored DM distribution and a set of scaling laws among local and global galaxy quantities emerges.

These scaling laws indicate (Salucci *et al.* 2007) that spirals have an Inner Baryon Dominance region where the stellar disk dominates the total gravitational potential, while the DM halo emerges farther out. At any radii, objects with lower luminosities have a larger dark-to-stellar mass ratio. The baryonic fraction in a spirals is always much smaller than the cosmological value $\Omega_b/\Omega_{matter} \simeq 1/6$, and it ranges between 7×10^{-3} to 5×10^{-2}, suggesting that processes such as SN explosions must have removed a very large fraction of the original hydrogen. Smaller spirals are denser, with their central density spanning 2 order of magnitudes over the mass sequence of spirals. The stellar mass-to-light ratio (in the B band) lies between 0.5 and 4 and increase with galaxy luminosity as $L_B^{0.2}$; in agreement with the values obtained by fitting the spirals SED with spectro-photometric models.

As far the structural properties of the DM distribution a most important finding is that the central surface density $\propto \mu_{0D} \equiv r_0\rho_0$, where r_0 and ρ_0 are the halo core radius and central spatial density, is nearly constant and independent of galaxy luminosity. Based on the co-added rotation curves of ~ 1000 spiral galaxies, mass models of individual dwarf irregular and spiral galaxies of late and early types with high-quality rotation curves and, galaxy-galaxy weak lensing signals from a sample of spiral and elliptical galaxies, we find that $\log \mu_{0D} = 2.15 \pm 0.2$, in units of $\log(\mathrm{M}_\odot\ \mathrm{pc}^{-2})$. This constancy transpasses the family of disk systems. We also show that the observed internal kinematics of Local Group dwarf spheroidal galaxies, are consistent with this value. Our results are obtained for galactic systems spanning over 14 magnitudes, belonging to different Hubble Types, and whose mass profiles have been determined by several independent methods. Very significantly, in the same objects, the approximate constancy of μ_{0D} is in sharp contrast to the systematical variations, by several orders of magnitude, of galaxy properties, including ρ_0 and central stellar surface density.

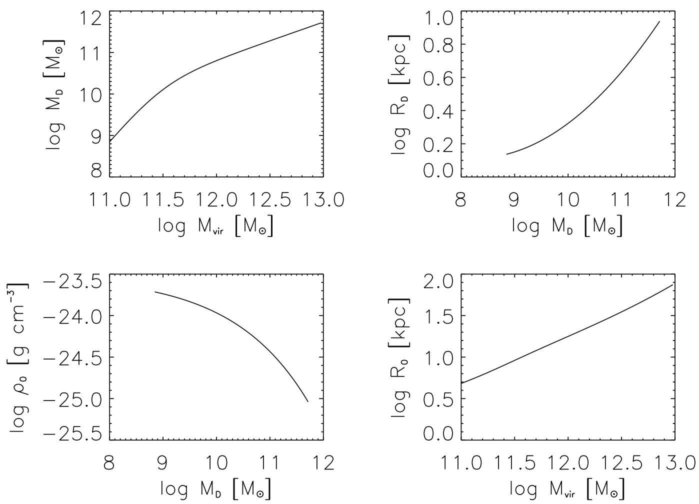

FIG. 6: Scaling relations between the structural parameters of the dark and luminous mass distribution in spirals.

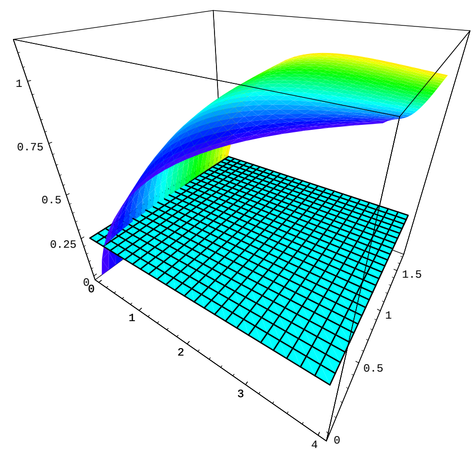

FIG. 7: The URC. The circular velocity as a function of radius (in units of R_D) and luminosity (halo mass) see Salucci et al 2007 for details.

The constancy of μ_{0D} can be related to the above scaling laws of spirals, as an example, let us define $M_{\rm h0}$ and $V_{\rm h0}$ is the enclosed halo mass inside r_0 and the halo circular velocity at r_0. we obtain $M_{\rm h0} \propto V_{\rm h0}^4$ which immediately reminds a sort of Tully-Fisher relation.

The evidence that the DM halo central surface density $\rho_0 r_0$ remains constant to within less than a factor of two over fourteen galaxy magnitudes, and across several Hubble types, does indicates that this quantity may hide the physical nature of the DM.Considering that DM haloes are (almost) spherical systems it is surprising that their central surface density plays a role in galaxy structure. One could wonder whether the physics we "witness" in the constancy of μ_{0D} be instead stored separately in r_0 and ρ_0. This interpretation has however a problem: r_0 and ρ_0 do correlate with the luminous counterparts, (the disk length-scale and stellar central spatial density) while μ_{0D} does not. Moreover, this evidence, is difficult to understand in an evolutionary scenario as the product of the process that has turned the primordial cosmological gas in the stellar structures we observe today. Such constancy in fact, must be achieved in very different galaxies of different morphology and mass, ranging from dark-matter-dominated to baryon-dominated objects. In addition, these galaxies have experienced significantly different evolutionary histories (e.g. numbers of mergers, significance of baryon cooling, stellar feedback, etc.).

The best explanation for our findings relays with the nature itself of the DM, as it seems to indicate recent theoretical work (de Vega et al., 2009, 2010.) Then, the distribution of matter galaxies has become a benchmark for understanding dark matter and the galaxy formation process. In particular, the universality of certain structural quantities and the dark-luminous coupling of the mass distributions, seem to bear the direct imprint of the Nature of the DM (Donato *et al.* 2009, Gentile *et al.* 2009).

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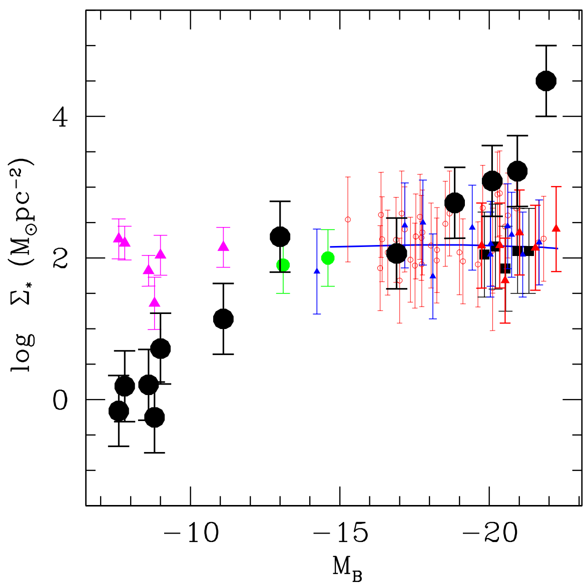

FIG. 8: Dark matter central surface density in units of $M_{\odot}\mathrm{pc}^{-2}$ as a function of galaxy magnitude, for different galaxies and Hubble Types. As a comparison the values of the same quantity of the stellar component is also shown (big filled circles).

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Galaxy properties, keV scale dark matter from theory and observations and the power of linear approximation

Galaxies are described by a variety of physical quantities:

(a) **Non-universal** quantities: mass, size, luminosity, fraction of DM, DM core radius r_0, central DM density ρ_0.

(b) **Universal** quantities: surface density $\mu_0 \equiv r_0\ \rho_0$ and DM density profiles. M_{BH}/M_{halo} (or halo binding energy).

The galaxy variables are related by **universal** empirical relations. Only one variable remains free. That is, the galaxies are a one parameter family of objects. The existence of such universal quantities may be explained by the presence of attractors in the dynamical evolution. The quantities linked to the attractor always reach the same value for a large variety of initial conditions. This is analogous to the universal quantities linked to fixed points in critical phenomena of phase transitions.

The universal DM density profile in Galaxies has the scaling property:

$$\rho(r) = \rho_0\ F\left(\frac{r}{r_0}\right) \quad , \quad F(0) = 1 \quad , \quad x \equiv \frac{r}{r_0}\ , \tag{3.4}$$

where r_0 is the DM core radius. As empirical form of cored profiles one can take Burkert's form for $F(x)$. Cored profiles **do reproduce** the astronomical observations (see contributions here by van Eymeren, Gentile and Salucci).

The surface density for dark matter (DM) halos and for luminous matter galaxies is defined as: $\mu_{0D} \equiv r_0\ \rho_0$, $r_0 =$ halo core radius, $\rho_0 =$ central density for DM galaxies. For luminous galaxies $\rho_0 = \rho(r_0)$ (Donato et al. 09, Gentile et al. 09).

Observations show an Universal value for μ_{0D}: independent of the galaxy luminosity for a large number of galactic systems (spirals, dwarf irregular and spheroidals, elliptics) spanning over 14 magnitudes in luminosity and of different Hubble types. Observed values:

$$\mu_{0D} \simeq 120\ \frac{M_\odot}{\mathrm{pc}^2} = 5500\ (\mathrm{MeV})^3 = (17.6\ \mathrm{Mev})^3 \quad , \quad 5\mathrm{kpc} < r_0 < 100\mathrm{kpc}\ .$$

Similar values $\mu_{0D} \simeq 80\ \frac{M_\odot}{\mathrm{pc}^2}$ are observed in interstellar molecular clouds of size r_0 of different type and composition over scales $0.001\,\mathrm{pc} < r_0 < 100$ pc (Larson laws, 1981). Notice that the surface gravity acceleration is given by μ_{0D} times Newton's constant.

The scaling form eq.(3.4) of the density profiles implies scaling properties for the energy and entropy.

The total energy becomes using the virial theorem and the profile $F(x)$:

$$E = \frac{1}{2}\,\langle U\rangle = -\frac{1}{4}\ G \int \frac{d^3r\ d^3r'}{|\boldsymbol{r}-\boldsymbol{r}'|}\ \langle\rho(r)\ \rho(r')\rangle = -\frac{1}{4}\ G\ \rho_0^2\ r_0^5 \int \frac{d^3x\ d^3x'}{|\boldsymbol{x}-\boldsymbol{x}'|}\ \langle F(x)\ F(x')\rangle \quad \Rightarrow \quad E \sim G\ \mu_{0D}^2\ r_0^3$$

Therefore, the energy scales as the volume.

The Boltzmann-Vlasov distribution function $f(\vec{p},\boldsymbol{r})$ for consistency with the profile form eq.(3.4), must scale as

$$f(\vec{p},\boldsymbol{r}) = \frac{1}{m^4\ r_0^3\ G^{\frac{3}{2}}\ \sqrt{\rho_0}}\ \mathcal{F}\left(\frac{\vec{p}}{m\ r_0\ \sqrt{G\ \rho_0}}, \frac{\boldsymbol{r}}{r_0}\right)$$

where m is the DM particle mass. Hence, the entropy scales as

$$S_{gal} = \int f(\vec{p},\boldsymbol{r})\ \log f(\vec{p},\boldsymbol{r})\ d^3p\ d^3r \sim r_0^3\ \frac{\rho_0}{m} = r_0^2\ \frac{\mu_{0D}}{m}$$

The **entropy** scales as the **surface** as it is the case for black-holes. However, for black-holes of mass M and area $A = 16\,\pi\ G^2\ M^2$, the entropy $S_{BH} = A/(4\ G) = 4\,\pi\ G\ M^2$. That is, the proportionality coefficients c between entropy and area are very different:

$$c_{gal} = \frac{S_{gal}}{r_0^2} \sim \frac{\mu_{0D}}{m} \quad , \quad c_{BH} = \frac{S_{BH}}{A} = \frac{1}{4\,G} \quad \text{which implies} \quad \frac{c_{BH}}{c_{gal}} \sim \frac{m}{\mathrm{keV}}\ 10^{36}$$

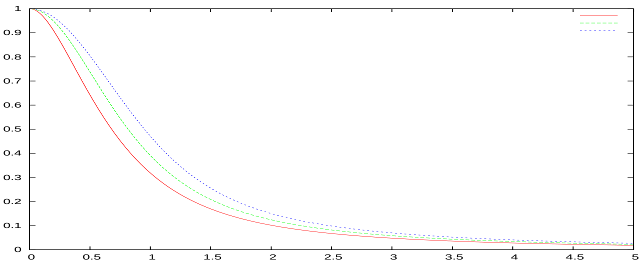

FIG. 9:

	Observed Values	Linear Theory	Wimps in linear theory
r_0	5 to 52 kpc	46 to 59 kpc	0.045 pc
ρ_0	1.57 to 19.3×10^{-25} $\frac{\mathrm{g}}{\mathrm{cm}^3}$	1.49 to 1.91×10^{-25} $\frac{\mathrm{g}}{\mathrm{cm}^3}$	0.73×10^{-14} $\frac{\mathrm{g}}{\mathrm{cm}^3}$
$\sqrt{\overline{v^2}}_{halo}$	79.3 to 261 km/sec	260 km/sec	0.243 km/sec

showing that the entropy per unit area of the galaxy is much smaller than the entropy of a black-hole. In other words the Bekenstein bound for the entropy of physical is well satisfied here.

In order to compute the surface density and the density profiles from first principles we have evolved the linearized Boltzmann-Vlasov equation since the end of inflation till today [2-3].

We depict in fig. 9 the density profiles vs. $x \equiv r/r_{lin}$ for fermions (green) and bosons (red) decoupling ultrarelativistic and for particles decoupling non-relativistically (blue). These profiles turn to be universal with the same shape as, for example, the Burkert profile. $r_{lin} \sim r_0$ depends on the galaxy and is entirely determined theoretically in terms of cosmological parameters and m [2-3].

We obtain in refs. [3,4] for the galaxy surface density in the linear approximation

$$\mu_{0\,lin} = 8261 \left[\frac{Q_{prim}}{(\mathrm{keV})^4}\right]^{0.161} \left[1 + 0.0489\ \ln \frac{Q_{prim}}{(\mathrm{keV})^4}\right] \mathrm{MeV}^3$$

where $0.161 = n_s/6$, n_s is the primordial spectral index and fermions decoupling UR were considered. Matching the **observed values** from spiral galaxies $\mu_{0\,obs}$ with this $\mu_{0\,lin}$ gives the primordial phase-space density $Q_{prim}/(\mathrm{keV})^4$ and from it the mass of the DM particle. We obtain $1.6 < m < 2$ keV for the dark matter particle mass [4].

Linear density profiles turn to be cored at scales $r \ll r_{lin}$. At intermediate regime $r \gtrsim r_{lin}$ we obtain [4],

$$\rho_{lin}(r) \overset{r \gtrsim r_{lin}}{=} \left(\frac{36.45\ \mathrm{kpc}}{r}\right)^{1+n_s/2} \ln\left(\frac{7.932\ \mathrm{Mpc}}{r}\right) \times \left[1 + 0.2416\ \ln\left(\frac{m}{\mathrm{keV}}\right)\right]\ 10^{-26}\ \frac{\mathrm{g}}{\mathrm{cm}^3} \quad , \quad 1 + n_s/2 = 1.482$$

The theoretical linear results **agree** with the universal empirical behaviour $r^{-1.6\pm0.4}$: M. G. Walker et al. (2009) (observations), I. M. Vass et al. (2009) (simulations).

We summarize in the Table the values for non-universal galaxy quantities from the observations and from the linear theory results. The larger and less denser are the galaxies, the better are the results from the linear theory for non-universal quantities. The linear approximation turns to improve for larger galaxies (i. e. more diluted) [4]. Therefore, universal quantities as profiles and surface density are reproduced by the linear approximation. The agreement between the linear theory and the observations is **remarkable**.

The last column of the Table corresponds to 100 GeV mass wimps. The wimps values strongly disagree by several orders of magnitude with the observations.

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Astrophysical interpretations of PAMELA/Fermi cosmic ray lepton data

The measurement of the positron fraction in the cosmic ray spectrum by the PAMELA satellite collaboration (Adriani:2008zr) has stimulated a lot of theoretical and phenomenological activity (for a slightly more extended review see (Serpico:1900zz)). The data show a rise between ~ 7 GeV and 100 GeV with a power-law index of about ~ 0.35, a feature that many have interpreted as an indirect signal of WIMP dark matter (DM) annihilations/decays. It is true that, on very general grounds, this behavior is at odds with the standard predictions for secondary positrons produced in the collisions of cosmic ray nuclei propagating in the inter-stellar medium (ISM), for which a decreasing fraction with E is expected (e.g. (Moskalenko:1997gh)). Barring *major* flaws in our understanding of cosmic ray astrophysics, it appears that when combined with information on the spectral slope for the overall $e^+ + e^-$ flux $\sim E^{-3}$, an additional source of positrons is required (Serpico:2008te). In particular, this conclusion can be hardly avoided after the publication of the quite hard spectrum of $e^+ + e^-$ measured by the Fermi satellite (fermiel).

Besides DM model building activity, the interest of these data has triggered a significant theoretical effort in revisiting the issue of *if* and *how plausibly* astrophysical sources can account for the observations, as well as possible further tests of these ideas. Although some models exist involving a relatively special astrophysical event in the neighborhood of the Earth in the recent past, by far the most popular astrophysical explanations invoke a whole class (or mechanism) of leptonic accelerators. Not surprisingly, virtually all models of this kind attribute ultimately the powering source to the death of massive stars as supernovae (SNe).

After the explosion of a SN, about $\sim 10^{51}$ erg of kinetic energy are released to the outwards-moving ejecta, powering (for thousands of years) shell-like SN Remnants (SNRs) (Reynolds08). The first-order, non-relativistic shock acceleration when the SNR expands in the ISM is the standard paradigm for the acceleration of both e^- and protons/nuclei, with energies from GeV to PeV (Blandford:1987pw).

In this framework, several possibilities have been explored in the literature. For example, one is that hard spectra of high energy e^+ and e^- are produced as secondaries in polar caps of SN whose progenitors were massive magnetic stars with winds, like Wolf Rayet and Red Super Giants (Biermann:2009qi). While energetics and spectral index requirements can be reproduced, it is interesting to ask the even more basic question of if peculiar field configurations and very massive stars are in fact needed at all, i.e. what are the predictions of the "baseline" model of SNRs. In fact, it was argued in (Blasi:2009hv) that already internal production and reacceleration in magnetic field configurations parallel to the normal to the shock front might be enough. In this model, the 'excess' is interpreted as the additional component due to positrons created as byproducts of hadronic interactions inside old SNRs, the standard source of the bulk of sub-TeV cosmic rays. Naively, one would expect internal production to be responsible for e^+ having a spectrum as hard as the proton one, which would translate into a flat e^+ fraction emerging at hundreds of GeV. However, if the environment has a diffusion coefficient $D(E)$ growing with energy (as expected), *reacceleration* involves secondary particles which are produced within a distance proportional to $D(E)$ from the shock (on both sides): the higher the energy, the more secondaries are involved in the process, which can in principle produce spectra harder than primary ones, although its quantitative details depend on environmental conditions during the late stages of evolution of SNRs. So, it is ultimately observations which should determine how relevant this process is in nature. Fortunately, due to the hadronic nature of the process, spallation unavoidably produces a large flux of antiprotons at $E > 100\,\text{GeV}$ (Blasi:2009bd) as well as signatures in secondary to primary nuclei (Mertsch:2009ph).

In most of the cases where a core-collapse SN takes place, however, one expects another "relic": a highly magnetized, fast spinning neutron star. The pulsar loses energy steadily by spinning-down, and this energy is transferred to electromagnetic channels, with some fraction going into relativistic electron-positron pairs. The acceleration of leptons stripped from the pulsar and the generation of a very high-energetic electromagnetic cascade is not hard to achieve. The spectral shape of the emission is however determined by a complicated series of plasma processes, related also to the location of the acceleration: $e^\pm$ and γ's are continuously produced, slowed-down and reconverted into each other by curvature radiation, inverse-compton scattering, photon-photon pair creation, etc. In turn, the $e^\pm$ pair wind of relativistic particles leaving the magnetosphere forms the so-called Pulsar Wind Nebula (PWN) (Gaensler:2006ua). For several pulsars, observations ranging from radio to X-ray data suggest that, at the termination shock produced when the PW interacts with the surrounding slower ejecta, efficient acceleration takes place, resulting into quite hard lepton spectra ($\sim E^{-1.5}$) extending up to hundreds of GeV. If a non-negligible fraction of this population makes its way out to the ISM, it is possible to reproduce quite effectively the data (pulsars). Compared with explanations

invoking SNRs, pulsars have the big advantage of being known to host a *large* population of non-thermal, relativistic pairs. On the other hand, detailed predictions of the spectral shape are rather uncertain and the theory of *relativistic* shocks in non-trivial magnetic field configurations and a medium containing pairs (possibly "polluted" by some protons/nuclei) is less well understood. Studies exist, however, where high efficiencies and hard spectra have been found, see e.g. (Amato:2006ts).

It is clear by now that the once-popular "standard model" of secondary cosmic ray positrons is insufficient in describing the data *at high energy*. However, it should be recognized that models relying only on ISM productions had been selected in the past due to their simplicity, rather than for the lack of astrophysical sources proposed to contribute to lepton fluxes (an example of 15 years-old study in this sense is (Atoian:1995ux)). These sources are nothing but the same objects shining in the sky in X and gamma-ray band. It should go without saying that they are *naturally* the first class of objects to look at for explaining unaccounted observations of cosmic ray fluxes. It is actually a sign of progress of the field that, thanks to observational improvements, it is now time to include them in theoretical models and fits. Concerning the implications for the WIMP paradigm for DM, the present data by themselves are rather neutral to it, since typical expectations for DM signals in antimatter fall a couple of orders of magnitude below the fluxes observed. On the other hand it is fair to conclude that, until a better understanding of the astrophysical sources is achieved, most antimatter signatures of WIMPs are far from robust (with the possible exception of sharp spectral edges or "large" numbers of low-energy antideuterons.)

Although there is still a long way to finally settle the interpretation of the data, the obvious next step would be to identify if the *main* contributors to the observed fluxes are leptonic accelerators (such as pulsars) or hadronic ones (such as SNRs). This might be a task for the forthcoming AMS-02 mission (AMS-02).

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Cosmological bounds on dark matter self-interactions

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Finite elastic dark matter self-interactions can be one of the ingredients to solve the puzzles of collisionless cold dark matter. In addition to a summary of the effects on dark matter halos, we present cosmological implications of a dark matter self-interaction energy density.

While the existence of dark matter (DM) is beyond all question, its properties are still subject to debate. Open issues are among others the number of galactic substructures and the cusp vs. core problem. Observational results on and attempts to resolve these shortcomings of collisionless cold DM (CDM) are presented in other lectures of this workshop. An additional effect related to these topics can be caused by finite DM elastic self-interactions (Spergel2000) which we will study in the following.

Substructures are colder halos embedded in larger hotter ones. Hence, they become heated and destroyed either by spallation or evaporation (Wandelt2000). But galactic halos as substructure of clusters have to survive at least for a Hubble time (Gnedin2001). Energy transfer occurs also from the hotter outer regions to the colder center of halos, so initial cusps are transformed to cores. To explain the observed core sizes of less dense dwarf galaxies one requires a larger cross section than compatible with cluster core sizes. A velocity dependent cross section can solve this dilemma (Dave2001, Yoshida2000). An additional effect of the isotropization of the velocity distribution in dense regions is the formation of spherical centers (Miralda2002). Cluster collisions allow to constrain the self-scattering strength by measuring the offset between the mass peak and the galaxy distribution and the mass to light ratio of the collided clusters (Randall2008).

TABLE II: Bounds on CDM self-scattering cross section from halo properties.

	$\sigma_{\mathrm{SI}}/m_{\mathrm{DM}}$ $\left[\mathrm{cm}^2/\mathrm{g}\right]$	Ref.
Core sizes	$\lesssim 0.5-5$	(Dave2001, Yoshida2000)
Galactic evaporation	$\lesssim 0.3$	(Gnedin2001)
Cluster ellipticity	$\lesssim 0.02$	(Miralda2002)
Bullet cluster	$< 0.7-1.25$	(Randall2008)

Very recently we highlighted in Ref. (Stiele2010) another consequence of elastic dark matter self-interactions, namely an additional energy density contribution.
We describe two particle interactions between scalar bosons (ϕ) or fermions (ψ) by minimal coupling to a vector field V_μ. The effective Lagrangian reads:

$$\mathcal{L}_\phi \;=\; \mathcal{D}^*_\mu\phi^*\mathcal{D}^\mu\phi - m_\phi^2\phi^*\phi - \tfrac{1}{4}V_{\mu\nu}V^{\mu\nu} + \tfrac{1}{2}m_{\mathrm{v}}^2V_\mu V^\mu, \tag{3.5a}$$

$$\mathcal{L}_\psi \;=\; \bar\psi\left(i\not{\mathcal{D}} - m_\psi\right)\psi - \tfrac{1}{4}V_{\mu\nu}V^{\mu\nu} + \tfrac{1}{2}m_{\mathrm{v}}^2V_\mu V^\mu\ , \tag{3.5b}$$

with $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ and $\mathcal{D}_\mu = \partial_\mu + ig_{\mathrm{v}\phi(\psi)}V_\mu$, where $g_{\mathrm{v}\phi(\psi)}$ is the $\phi(\psi)$-V coupling strength. The interaction is repulsive which avoids an enhancement of the annihilation cross-section due to the formation of bound states. The total energy density and pressure of the self-scattering DM can be determined from the energy-momentum tensor to be

$$\varrho_{\phi(\psi)} = \varrho^{\mathrm{free}}_{\phi(\psi)} + \frac{g^2_{\mathrm{v}\phi(\psi)}}{2m_{\mathrm{v}}^2}\,n^2_{\phi(\psi)}\ . \tag{3.6}$$

We denote the particle masses $m_{\mathrm{SIDM}} \equiv m_{\phi(\psi)}$, $m_{\mathrm{SI}} \equiv m_{\mathrm{v}}$, and define the coupling constant $\alpha_{\mathrm{SI}} \equiv g^2_{\mathrm{v}\phi(\psi)}/2$, so that the energy density and pressure contributions from DM self-interactions read

$$\varrho_{\mathrm{SI}} = \frac{\alpha_{\mathrm{SI}}}{m_{\mathrm{SI}}^2}\,n^2_{\mathrm{SIDM}} = p_{\mathrm{SI}}\ , \tag{3.7}$$

with $m_{\rm SI}/\sqrt{\alpha_{\rm SI}}$ as the energy scale of the self-interaction. For weak interactions the interaction strength is $m_{\rm weak}/\sqrt{\alpha_{\rm weak}} \sim 300\,{\rm GeV}$ and for strong interactions $m_{\rm strong}/\sqrt{\alpha_{\rm strong}} \sim 100\,{\rm MeV}$.
Refs. (Narain2006, Agnihotri2009) explored implications of this self-interaction energy density contribution on the mass-radius relation of compact stars made of self-interacting DM.
The equation of state (3.7) as input to the Friedmann equations determines the scaling behaviour of the self-interaction energy density with the scale factor a:

$$\varrho_{\rm SI} \propto a^{-6}\ . \tag{3.8}$$

Hence, $\varrho_{\rm SI}$ shows the steepest decrease and the universe could be in a self-interaction dominated epoch prior to radiation domination in the very early universe.
Eqs. (3.7) and (3.8) imply that $n_{\rm SIDM} \propto a^{-3}$. So the self-interacting DM particles have to be warm for decoupling during self-interaction domination and can only be cold if they decouple after the self-interaction dominated era, which can last at the latest until shortly before primordial nucleosynthesis (see below). In any case, the recently highlighted DM particle mass scale in the keV range (deVega2010, Boyanovsky2008) is an attractive particle candidate for self-interacting DM.

Primordial nucleosynthesis (BBN) is the physical process of choice to constrain the self-interaction strength, since the element abundances are sensitive to the energy content of the universe via the expansion rate $H \propto \varrho^{1/2}$. The relative contribution of the self-interaction energy density is largest at the earliest stage of BBN, the freeze-out of the neutron to proton number ratio. Nearly all neutrons available for the nucleosynthesis processes are incorporated into ^{4}He, so we can translate the upper limit on the primordial ^{4}He abundance from observations $Y_{\rm P} < 0.255$ (2σ, (Steigman2007)) into the following constraint on the DM self-interaction strength (Stiele2010):

$$\frac{m_{\rm SI}}{\sqrt{\alpha_{\rm SI}}} \gtrsim 1.70\,{\rm keV} \times \frac{F^0_{\rm SIDM}}{m_{\rm SIDM}/1\,{\rm keV}}\ . \tag{3.9}$$

The relative amount of SIDM $F^0_{\rm SIDM} \equiv \Omega^0_{\rm SIDM}/\Omega^0_{\rm DM}$ serves to include the possibility of multiple DM components.
Even an additional energy density contribution of DM self-interactions of the strength of the strong interaction ($m_{\rm strong}/\sqrt{\alpha_{\rm strong}} \sim 100\,{\rm MeV}$) is consistent with the primordial element abundances.

Which further consequences can a self-interaction dominated universe before BBN have? A physical process happening during this early stage is the decoupling of the DM particles. Chemical decoupling occurs when the expansion rate of the universe exceeds the DM annihilation rate $\Gamma_{\rm A} = n_{\rm DM}\,\langle\sigma_{\rm A} v\rangle$. In a universe that is dominated by a WDM self-interaction energy density contribution, also the expansion rate $H \propto \varrho^{1/2}$ is proportional to the WDM particle density , so that the WDM annihilation cross-section is independent on the particle parameters but determined by the elastic self-interaction strength:

$$\sigma^{\rm WDM}_{\rm A} \approx 7.45 \times 10^{-7} \times \frac{100\,{\rm MeV}}{m_{\rm SI}/\sqrt{\alpha_{\rm SI}}}\,\sigma_{\rm weak}\ , \tag{3.10}$$

with $\sigma_{\rm weak} \approx 1.24 \times 10^{-39}\,{\rm cm}^2$. Hence, WSIDM decoupling in a self-interaction dominated universe reproduces naturally and consistently the 'super weak' inelastic coupling between the WSIDM and baryonic matter.
For decoupling of a collisionless CDM component, usually represented by WIMPs, in a self-interaction dominated universe the natural scale of the velocity weighted mean annihilation cross-section becomes (Stiele2010)

$$\begin{aligned}\langle\sigma_{\rm A} v\rangle_{\rm CDM} \ &\approx\ 2.77 \times 10^{-23}\,{\rm cm}^3\,{\rm s}^{-1} \\ &\quad\times \frac{m_{\rm CDM}/10\,{\rm TeV}}{m_{\rm WDM}/1\,{\rm keV}}\,\frac{1\,{\rm MeV}}{m_{\rm SI}/\sqrt{\alpha_{\rm SI}}}\,\frac{F^0_{\rm WDM}}{1-F^0_{\rm WDM}}\ .\end{aligned} \tag{3.11}$$

Hence, the natural scale of the CDM annihilation cross-section depends beside the WDM elastic self-interaction strength also linearly on the CDM particle mass. All in all the natural scale of CDM decoupling can be increased by some orders of magnitude. This is in contrast to the 'WIMP miracle' (meaning that they actually aren't so weakly interacting) and interestingly enough, such boosted CDM annihilation cross-sections are able to explain the high energy cosmic-ray electron-plus-positron spectrum measured by Fermi-LAT and the excess in the PAMELA data on the positron fraction (e.g. (Bergstroem2009B)).

Another consequence of an early self-interaction dominated epoch may concern structure formation. A relativistic analysis of ideal fluid cosmological perturbations reveals for self-interaction dominated DM the following evolution of the density contrast δ in the subhorizon limit ($k_{\rm ph}/H \gg 1$):

$$\delta_{\rm SIDM} \propto a \cdot \left(A\cos(a^2 - 3\pi/4) + B\sin(a^2 - 3\pi/4)\right)\ , \tag{3.12}$$

i.e. an oscillation with linearly growing amplitude (Hwang1993). However, any increase in the density contrast in WSIDM produced will be washed out either due to collisional self-damping or due to free streaming.
But a subdominant collisionless CDM component allows some increase in density fluctuations to be stored (Stiele2010):

$$\delta_{\rm CDM} = a \cdot \left(C / a_k^{\rm in\,2} \right) + D \, . \tag{3.13}$$

This means that subhorizon collisionless CDM density fluctuations will also grow linearly during a self-interaction dominated phase. Thus fluctuations at low masses in the matter power spectrum are enhanced. They are limited by the comoving wavenumber that is equal to the Hubble scale at self-interaction–radiation equality, coresponding to $\sim 1.4 \times 10^{-3} M_\odot$ as the largest structures that can be affected (Stiele2010).

Another physical process in the early universe, maybe influenced if happening during a self-interaction dominated epoch is the QCD phase transition, which nature has recently received new attention (Boeckel2009).

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Non-circular motions and the cusp-core discrepancy in dwarf galaxies

The cusp-core discrepancy, one of the major problems in galaxy evolution, is still causing many debates between observers and cosmologists. Cold Dark Matter (CDM) simulations predict cuspy haloes in the central parts of galaxies with a density distribution described by a power law $\rho(r) \sim r^{\alpha}$ with α ranging from -1 (e.g., [7]) to -1.5 (e.g., [6]). This cusp leads to a steeply rising rotation curve. However, observations of dark matter dominated dwarf and low surface brightness (LSB) galaxies show that their rotation curves rise less steeply than predicted by CDM simulations (e.g., [1]). At small radii (typically a few kpcs), the mass distribution can better be described by a central, constant-density core (e.g., [4]). Observational shortcomings like the effect of beam smearing or slit misplacement have been claimed to be responsible for flattening the rotation curves in the inner 1 kpc. Furthermore, deviations from the assumed circular orbits, so-called non-circular motions might also lead to an underestimate of the slope.

We chose a sample of six nearby irregular dwarf galaxies and obtained H I synthesis observations with sufficiently high (i.e., below 1 kpc) spatial resolution. We derived the kinematic parameters by performing a tilted-ring analysis of the Hermite velocity fields. In order to quantify the contribution of non-circular motions to the derived rotation curves, we performed a harmonic decomposition up to third order. After that, the rotation curves were decomposed into contributions from gas, stars, and dark matter, where the distribution of the dark matter was fitted with both NFW and pseudo-isothermal (ISO) halo profiles. We then performed a χ^2 minimisation to find the best fit.

Figure 10 shows the quadratically-added amplitudes of the non-circular components up to third order *vs.* the distance from the dynamic centre (upper row). All sample galaxies have non-circular motions with absolute amplitudes below $10\,\mathrm{km\,s^{-1}}$, often below $5\,\mathrm{km\,s^{-1}}$, independent of the radius we look at. The lower row of Fig.10 shows the quadratically-added amplitudes normalised by the local rotation velocity. According to simulations by [5] (and ref. therein), non-circular motions add up to about 50% of the local rotation velocity at a radius of 1 kpc and even more below 1 kpc. Here, it can be seen that the non-circular motions contribute less than 25% to the local rotation velocity (again independent of the radius). This means that the non-circular motions in our sample galaxies are not high enough to significantly change the slope of the rotation curves.

The results from the mass decomposition can be summarised as follows: χ^2_{red} is in almost all cases much larger when we use the NFW model as a representation of the dark matter distribution. The adapted parameters of the ISO model are plausible and follow the recent finding of a constant central surface density ([2]). We found values for the slope α of -0.43 up to 0.03 (see Fig. 11), which is within the uncertainties of the value measured from the observations of LSB galaxies, -0.2 ± 0.2 ([1]).

We can rule out a significant contribution of non-circular motions in the central parts of our sample galaxies. The slopes can better be described by the empirically derived ISO halo. Therefore, we conclude that the measured cores are not hidden cusps. This result is in agreement with many other publications (Fig. 11). For further details see [3].

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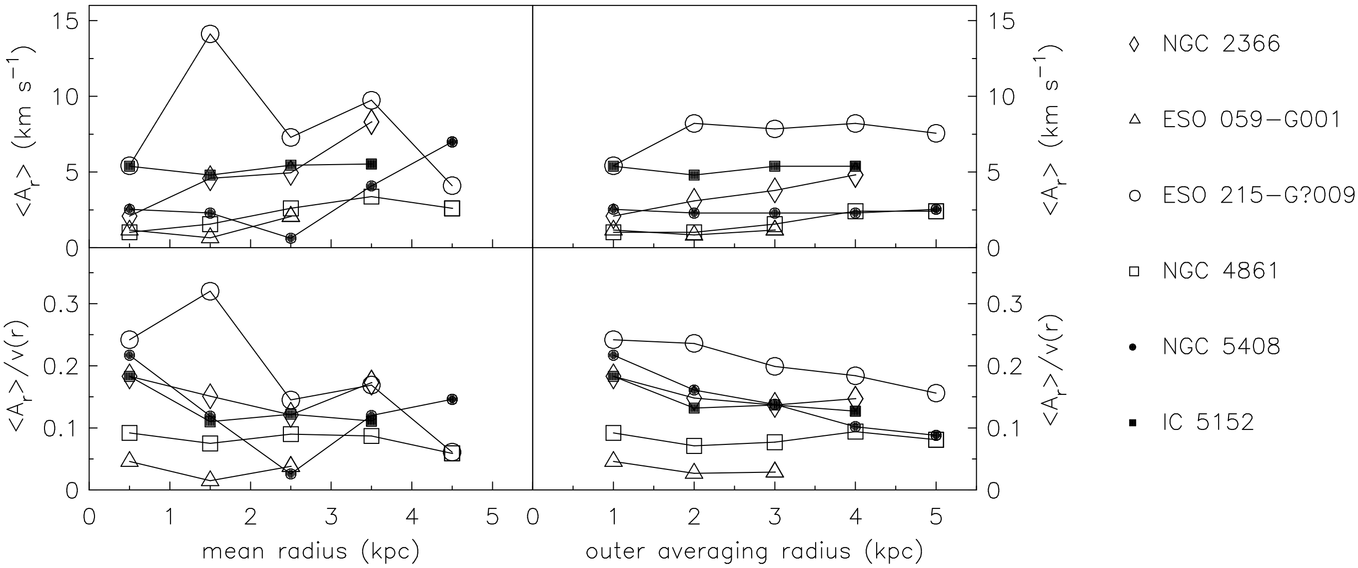

FIG. 10: **Upper left panel:** the mean values of the quadratically-added amplitudes of the non-circular motions within rings of 1 kpc width (i.e., $0 < r < 1$ kpc, $1 < r < 2$ kpc, ..., $4 < r < 5$ kpc) for each galaxy (indicated by different symbols). **Upper right panel:** the same as the upper left panel, but the amplitudes of the non-circular motions are averaged within rings of increasing radius (i.e., $0 < r < 1$ kpc, $0 < r < 2$ kpc, ..., $0 < r < 5$ kpc). **Lower left and right panel:** like the upper left and right panel, but the amplitudes of the non-circular motions are normalised by the local rotation velocity.

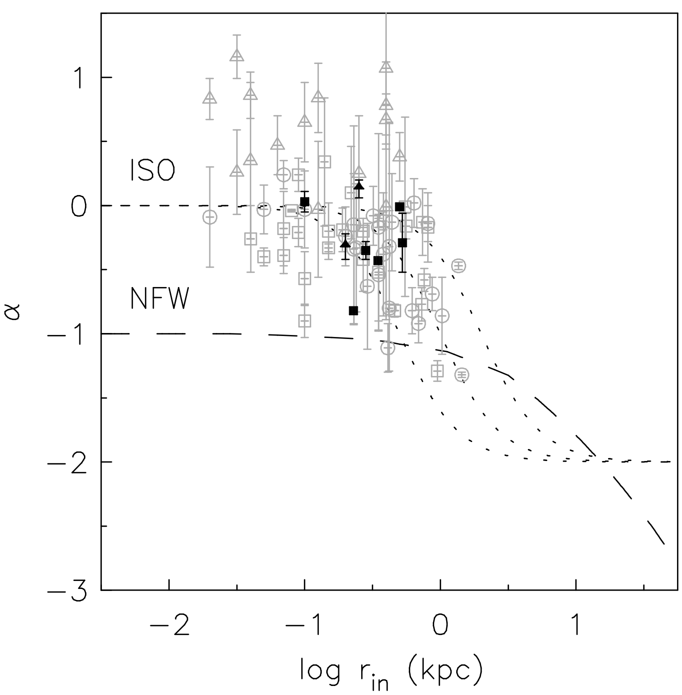

FIG. 11: The inner slope α of the dark matter density profiles plotted against the radius of the innermost point. Grey symbols and black triangles present observations of dwarf and LSB galaxies performed by different observers (see [3] for details). Our results are overplotted with black squares.

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Determination of the local DM density in our Galaxy

The best evidence for Dark Matter (DM) in galaxies is usually provided by rotation velocities, which do not fall off fast enough at large distances from the Galactic centre (GC). For a flat rotation curve the DM density has to fall off like $1/r^2$ at large distances, which is indeed expected from the virial theorem for a gas of gravitational interacting particles.
A reliable determination of the local DM density is of great interest for direct DM search experiments, where elastic collisions between WIMPs and the target material of the detector are searched for. This signal is proportional to the local density.

The local DM density can be determined from the rotation velocities of Galactic objects which are proportional to the gravitational potential of the Milky Way (MW). The gravitational potential is connected to the density distribution of the Galaxy via Poisson's equation. The first step of the determination of the local DM density is the assumption of the density distributions of the two different matter contributions to the MW: the luminous and the dark matter. Then, the parameters of these distributions are fitted to experimental constraints obtained from Galactic kinematics.

The density distribution of the luminous matter of a spiral galaxy is split into two parts, the Galactic disc and the Galactic bulge. The parametrization of the density distribution of the bulge is adapted from the publication by (Cardone:2005)

$$\begin{aligned} \rho_b(r,z) &= \rho_b \cdot \left(\frac{\tilde{r}}{r_{0,b}}\right)^{-\gamma_b} \cdot \left(1+\frac{\tilde{r}}{r_{0,b}}\right)^{\gamma_b-\beta_b} \exp\left(-\frac{\tilde{r}^2}{r_t^2}\right) \\ \tilde{r}^2 &= \sqrt{x^2+y^2+(z/q_b)^2}. \end{aligned} \tag{3.14}$$

The parameters of the Galactic bulge are obtained from the consideration of the velocity distribution in the Galactic disc near the GC. The parametrization of the Galactic disc is taken from the publication by Sparke

$$\rho_d(r,z) = \rho_d \cdot \exp(-r/r_d) \cdot \exp(-z/z_d). \tag{3.15}$$

The parameter ρ_d describes the density of the Galactic disc at the GC while $\mathrm{r_d}$ and $\mathrm{z_d}$ describe the scale parameter in radial and vertical direction.
The Galactic DM contribution is distributed within a large DM halo which extends the visible matter by an order of magnitude. It is commonly believed that the profile of a DM halo can be well fitted by the universal function

$$\begin{aligned} \rho_\chi(r) &= \rho_{\odot,DM} \cdot \left(\frac{\tilde{r}}{r_\odot}\right)^{-\gamma} \cdot \left[\frac{1+\left(\frac{\tilde{r}}{a}\right)^\alpha}{1+\left(\frac{r_\odot}{a}\right)^\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}, \\ \tilde{r} &= \sqrt{x^2+\frac{y^2}{\epsilon_{xy}^2}+\frac{z^2}{\epsilon_z^2}}. \end{aligned} \tag{3.16}$$

Here, a is the scale radius of the density profile, which determines at what distance from the centre the slope of the profile changes, ϵ_xy and ϵ_z are the eccentricities of the DM halo within and perpendicular to the Galactic plane and $\mathrm{r}_\odot$ is the Galactocentric distance of the solar system.

The local DM density is determined from the kinematics of stars and interstellar gas. The observation of the Galactic kinematics depends on the standard frame of rest which means the Galactocentric distance of the Solar System $r_\odot$ and its rotation velocity $v_\odot$. These values are obtained from the observation of Sgr A* which is probably the centre of the Galaxy because of its own small velocity. The distance between the Sun and the GC has been determined to Gillessen:2008:

$$r_\odot = 8.33 \pm 0.35 \text{ kpc}, \tag{3.17}$$

in agreement with previous authors Ghez:2008. With this Galactocentric distance one finds a rotation velocity of the Sun

$$v_{\odot} = 244 \pm 10 \text{ km s}^{-1}, \tag{3.18}$$

which is consistent with recent observations of Galactic masers in Bovy:2009, who used data from the Very Long Baseline Array (VLBA) and the Japanese VLBI Exploration of Radio Astronomy (VERA).

The experimental measurements to constrain the local DM density are i) the total matter density at the Sun, ii) the total Galactic mass within a Galactocentric distance of 60 kpc, iii) the surface density of the luminous and iv) the total matter. The velocity distribution in the Galactic disc and the height of the interstellar gas distribution are used to constrain the density distribution in radial and in z direction.

The total matter density at the Sun is determined from the vertical motion of stars to be $\rho_{\odot,\mathrm{tot}}(z=0) = 0.102 \pm 0.010$ M$_{\odot}$ pc^{-3}. This measurement was first proposed and performed by Jan Oort in 1932.

The surface density of the luminous matter at the Sun is used to constrain the matter contribution of the Galactic disc. It is obtained from star counts to be $\Sigma_{\mathrm{vis}} = 35 - 58$ M$_{\odot}$ pc^{-2} (Naab:2005). The total surface density is determined in the paper by Holmberg:2004 from the modeling of the vertical gravitational potential. This analysis resulted in $\Sigma(< 1.1 \text{ kpc}) = 74 \pm 6$ M$_{\odot}$ pc^{-2}.

The total mass of the MW within a Galactocentric distance of 60 kpc is obtained from the observation of the kinematic of halo stars. Using a large sample of 2400 blue horizontal-branch stars from the Sloan Digital Sky Survey in the halo (z > 4 kpc, R< 60 kpc) and comparing the results with N-body simulations using an NFW profile from Xue:2008 find

$$\mathrm{M}_{\mathrm{R}<60 \text{ kpc}} = 4.0 \pm 0.7 \cdot 10^{11} \mathrm{M}_{\odot}, \tag{3.19}$$

which corresponds to $\mathrm{M}_{\mathrm{tot}} = 1.0^{+0.3}_{-0.2} \cdot 10^{12}$ M$_{\odot}$.

The experimental data of the rotation velocity distribution in the Galactic disc, the so-called rotation curve (RC) of the MW, is adapted from the publication by Sofue:2008, where different measurements with different tracers are summarized, and the publication by Binney. The RC shows a change of slope at a Galactocentric distance of about 10 kpc.

A χ^2 fit of the density distribution is performed for cored and cuspy halo profiles. The experimental data allows no differentiation between a cored and a cuspy DM halo since the density distribution in the GC is dominated by the luminous matter. The local DM density is obtained to be $\rho_{\mathrm{DM},\odot} = 0.3 \pm 0.1$ GeV cm^{-3}. For oblate haloes with $\epsilon_z = 0.7$ the local DM density is $\rho_{\mathrm{DM},\odot} \approx 0.5$ GeV cm^{-3} (Weber:2009). However, a poor description of the RC is found.

In order to describe the change of slope in the RC and the height of the interstellar gas distribution an additional DM component in the Galactic disc is necessary. The gravitational influence of two doughnut-shaped DM rings (an inner ring at $r \approx 4$ kpc and a outer ring at $r \approx 13$ kpc) leads to a change of slope in the RC at about 10 kpc as can be seen in Figure 12. This can be understand as follows. The gravitational pull of the outer rings decelerate rotating objects at the inner Galaxy and accelerates objects beyond the outer ring. The outer ring also influences the gas flaring, i.e. the increase of the gas layer with increasing distance from the Galactic centre. This is simply to the decreasing gravitational potential. However, a ring of DM in the outer Galaxy will increase locally the gravitational potential and thus reduce the gas layer. This reduced gas flaring has indeed be observed (Kalberla:2007), and provides independent evidence for a ring of DM. An enhancement of DM in the Galactic disc, so-called 'dark discs', have indeed been predicted by recent N-body simulations of the accretion of satellite galaxies onto early galactic discs (Purcell:2009). Coplanar tidal streams resulting from the disruption of the satellite galaxy only feel the radial gradient of the gravitational potential of the Galaxy, which leads to ringlike structures with a much longer lifetime than the tidal streams in the halo.

The study of the stellar population of the outer disc (Newberg:2001) based on the observation of the fields at the Galactic anticentre with the Sloan Digital Sky Survey (SDSS) showed a ring structure outside the main spiral structure of the Galactic disc. This ring, which is unconnected to the spiral structure in the inner disc, is called outer ring or Monoceros ring. An enhancement of stars along this ring was discovered in the Canis Major constellation (Bellazzini:2003, Bellazzini:2005) at Galactic longitudes around 240°. This overdensity was interpreted as a dwarf galaxy, called Canis Major Dwarf, which could be the progenitor of the tidal stream. The velocity dispersion of the Canis Major stars is very low which further confirms their common origin (Martin:2005) and is not explainable with a warp of the Galactic disc (Martin:2003).

In summary, the experimental constraints can be met by a cuspy and a cored profile. A differentiation between a cusp or a core in the GC is not possible since the density distribution in the centre is dominated by the visible matter. The local DM density is determined to be $\rho_{\mathrm{DM},\odot} = 0.3 \pm 0.1$ GeV cm^{-3} for spherical haloes and $\rho_{\mathrm{DM},\odot} \approx 0.7$ GeV cm^{-3} for oblate haloes. The rotation curve and the height of the interstellar gas distribution can be described assuming an additional ringlike DM component in the Galactic disc which yields $\rho_{\mathrm{DM},\odot} \leq 1.0$ GeV cm^{-3}.

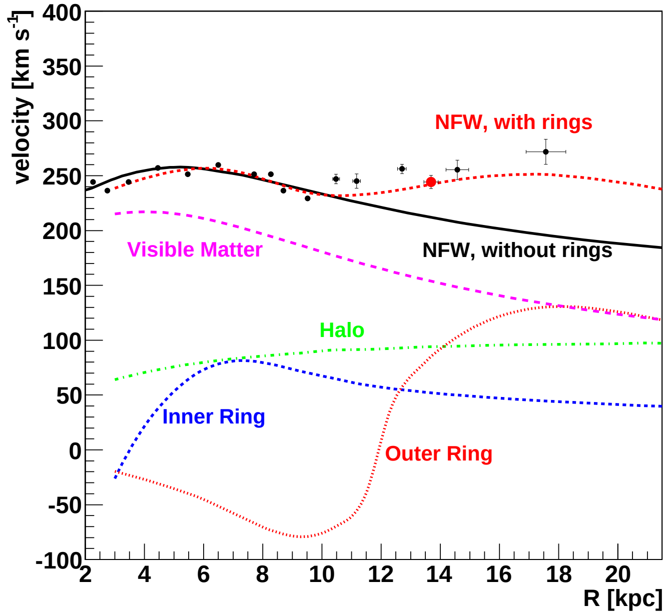

FIG. 12: Rotation curve of the MW. The change of slope at a Galactocentric distance of about 10 kpc is clearly visible. A cuspy NFW profile in combination with two DM rings in the Galactic disc yields a good description of the experimental data.

A large uncertainty of the local DM density is found which results from the large uncertainty of the surface density of the visible matter. Therefore, the accuracy of the estimation of the counting rate in direct DM search experiments strongly depends on the determination of the surface density of the visible matter.

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IV. SUMMARY AND CONCLUSIONS OF THE WORKSHOP BY H J DE VEGA AND N G SANCHEZ

Participants came from Europe, North and South America, Russia, India, Korea. Discussions and lectures were outstanding. Inflection points in several current research lines emerged.

The participants and the programme represented the different communities doing research on dark matter:

- Observational astronomers
- Computer simulators
- Theoretical astrophysicists not doing simulations
- Astroparticle theorists

The **hottest** subject of discussion was:
What is the mass of the DM particle and what is its nature?

A word about notation. We talk about 'keV scale DM particles' instead of WDM which is less precise. Also, we use the more precise name 'wimp simulations' indicating simulations with DM particles heavier than a GeV instead of CDM. Since keV scale DM particles are non relativistic for $z < 10^6$ they also deserve the name of cold dark matter.

Some conclusions are:

- Facts and status of DM: Astrophysical observations point to the existence of DM. Despite of that, proposals to replace DM by modifing the laws of physics did appeared, however notice that modifying gravity spoils the standard model of cosmology and particle physics not providing an alternative.
- The DM research appears to split in three sets: (a) Particle physics DM: building models beyond the standard model of particle physics, dedicated laboratory experiments, annihilating DM. All concentrated on wimps. (b) Astrophysical DM: astronomical observations, astrophysical models. (c) Numerical cosmological simulations. The results of (b) and (c) do not agree with each other at small scales.
- The DM domain of research is mature: there exists from more than 20 years a large scientific community working in the subject; there exists a large number of astronomical observations, there exists astrophysical models which agree with the observations; all dedicated particle experiments of direct search of wimps from more than twenty years gave nil results; many different groups perform N-body cosmological computer simulations and an important number of conferences on DM and related subjects is held regularly.
- Something is going wrong in the DM research. What is going wrong and why?
- Astronomical observations strongly indicate that **dark matter halos are cored till scales below 1 kpc**. More precisely, the measured cores **are not** hidden cusps.
- Numerical simulations with wimps (particles heavier than 1 GeV) without **and** with baryons yield cusped dark matter halos. Adding baryons do not alleviate the problems of wimps simulations, on the contrary adiabatic contraction increases the central density of cups worsening the discrepancies with astronomical observations.
- The observed galaxy surface density appears to be universal within $\sim 10\%$ with values around 100 $M_\odot/\text{pc}^2$.
- The results of numerical simulations must be confronted to observations. The discrepancies of wimps simulations with the astronomical observations at small scales $\lesssim 100$ kpc **keep growing and growing**: satellite problem (for example, only 1/3 of satellites predicted by wimps simulations around our galaxy are observed), voids problem, peculiar velocities problem (the observations show larger velocities than wimp simulations), size problem (wimp simulations produce too small galaxies).
- The use of keV scale DM particles in the simulations alleviate all the above problems. For the core-cusp problem, setting the velocity dispersion of keV scale DM particles seems beyond the present resolution of computer simulations. Analytic work in the linear approximation produces cored profiles for keV scale DM particles and cusped profiles for wimps.
- The features of electrons and positrons observed recently by Auger, Pamela and HESS can all be explained as having their origin in the explosions and winds of massive stars in the Milky Way. All these observations of cosmic ray positrons and the like are due to normal astrophysical processes, and do not require special decaying or annihilation of heavy DM particles.

- None of the predictions of wimps simulations at small scales (cusps, substructures, ...) have been observed.
- Model-independent analysis of DM from phase-space density and surface density observational data plus theoretical analysis points to a DM particle mass in the keV scale.
- As a conclusion, the dark matter particle candidates with large mass (~ 100 GeV, the so called 'wimps') became strongly disfavored, while light (keV scale mass) dark matter are being increasingly favoured both from theory, numerical simulations and a wide set of astrophysical observations.
- Many researchers (including several participants to this Workshop) continue to work with heavy DM candidates (mass $\gtrsim 1$ GeV) despite the **growing** evidence that these DM particles do not reproduce the small scale astronomical observations ($\lesssim 100$ kpc). Why? [The keV scale DM particles naturally produce the observed small scale structure]. The answer to this strategic question appears not to be strictly scientific but it is anyway beyond the scope of these scientific conclusions. Such strategic question was present in many animated discussions during the Workshop.

It should be recalled that the connection between small scale structure features and the mass of the DM particle directly follows from the value of the free-streaming length l_{fs} and is well known. Structures smaller than l_{fs} are erased by free-streaming. DM particles with mass in the keV scale give $l_{fs} \sim 100$ kpc while 100 GeV DM particles produce an extremely small $l_{fs} \sim 0.1$ pc. While $l_{fs} \sim 100$ kpc is in nice agreement with the astronomical observations, a l_{fs} a million times smaller requires the existence of a host of DM smaller scale structures till a distance of the size of the Oort's cloud in the solar system. No structures of this type have ever been observed.

All the Workshop lectures can be find at:

http://chalonge.obspm.fr/Programme_CIAS2010.html

V. LIVE MINUTES OF THE WORKSHOP BY PETER BIERMANN

Peter Biermann[1,2,3,4,5]
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Dark matter has been detected 1933 (Zwicky) and basically behaves like a non-EM-interacting self-gravitating gas of particles. Observational arguments for it are the rotation curves of disk galaxies, the stability of thin disks, the hot gas in galaxies, galaxy groups and clusters of galaxies, as well as the Large Scale Structure of the Universe.

A. Observations of galaxies

This allows to go back to galaxy data to derive the key properties of the dark matter particle: Recent observations, Hogan & Dalcanton (2000 PRD, 2001 ApJ), Gilmore et al. (from 2006 MNRAS, 2007 ApJ, etc.), Strigari et al. (2008 Nature), clearly point to some common properties of galaxy cores.

B. Our galaxy

Markus Weber, KIT: Measuring the DM particle density: runs through the Jan Oort and Maarten Schmidt arguments, Holmberg & Flynn 2004 (0405155); uses the older data from Brunthaler; mentions a paper by Merrifield 1992 about the scale-height of gas in the GC region; gives indeed about 100 pc; seems to ignore the old Kahn & Woltjer arguments on mass within a few hundred kpc; obtain $\rho_{DM} = 0.3 \pm 0.1 GeV/cc$, in agreement with Salucci et al. (2010) - 1003.3101; using a different method they get 0.389 $\pm$ 0.025 GeV/cc (Bayesian Markov chain algorithm); DM rings can be produced by the infall of dwarf galaxies, and distort the rotation curves; he works with W. de Boer at Karlsruhe.

C. Clusters of galaxies

Alfonso Cavaliere, Rome: He argues that the intra-cluster medium constitutes the best plasma overall. ICP = Intra Cluster Plasma; uses entropy description to test plasma model for clusters, Molendi & Pizzolato 2001; Pratt et al. 2010; entropy eroded by cooling, increased by shocks; Voit 2005, Arnaud et al. 2009; Fusco-Femiano, Lapi, Cavalieri 2009; entropy floor and entropy ramp from central heating/cooling, and infall shock; results A2199 central ICP cold, A2597 cold, A1689 cold, A1656 hot, A2256 hot, A644 hot: in cold case DM extended, old, z_t near 2; in hot case DM compact, young, z_t near 0.5; deep mergers supply entropy, energy; M87 Forman et al. 2006, 15 kpc ring seen corresponding to explosion about 10^7 years ago, with about 10^{59} ergs; Her A cluster McNamara & Nulsen 2008, shocks at 200 kpc; Voit & Donahue 2005; Ciotti & Ostriker 2007; Tabor & Binney 1998; Cavalieri & Lapi 2008; Tozzi & Norman 2001; Vikhlinin et al. 2009, Lau et al. 2010, Molnar et al. 2010; Inogamov & Sunyaev 2003; Reisprich et al. 2009, Bautz et al. 2009, Geroeg et al. 2009,..; he confirms that AGN probably inject less energy than just major mergers – I wonder whether that boils down to a tautology, since each major merger leads to feeding of a central BH.

D. Small galaxies

Matthew Walker, Cambridge, UK: Diemand, Kuhlen, Madau et al 'Via Lactea II'; Belokurov et al. 2007; by definition star clusters do not need DM, dwarf galaxies do; globular clusters have a scale of order 10 pc, dwarf galaxies typically 100 pc; globular clusters single spike of star formation, dwarf galaxies continuous star formation; dwarf galaxies are entire dominated by DM, since they have about the same stellar luminosity; M/L ratio ranges up to hundreds in solar units, so they are the darkest stellar systems; best for DM detection; observes in the Magnesium triplet absorption lines; uses cross-correlation with a template spectrum; Walker et al. 2009; pressure supported systems are analyzed by velocity dispersion, gives flat curves; similar to normal galaxies show more matter than is seen directly; then analyzes data from dwarf galaxies, basically the details which Gerry Gilmore explained at previous Chalonge meetings; strongest constraint from using the mass within that radius, which contains half the light; see also

Penarrubia et al. 2007, 2008; Wolf et al. 2009, 2010; $M(r_{half}) = \mu\, r_{half}\, \sigma^2,\ \mu = 580\, M_\odot\, \mathrm{pc}^{-1}\, \mathrm{km}^{-2}\mathrm{s}^2$; isothermal sphere ruled out; last author of Strigari et al. (2008), but now critical: claim then $M_{DM}(< 300pc) \simeq 10^7\, M_\odot$; for really small galaxies $M(< 300pc)$ not really well defined by data, used a math extrapolation; uses an extrapolation; the smaller galaxies may not even have a total of 10^7 solar masses; but over several orders of magnitude the relationship in Strigari et al. (2008) is a good approximation, just not for the smallest galaxies; Marc Aaronson 1983 showed that dwarf galaxies are DM dominated, then based on three stars; Mateo 1993, 1008; ultrafaint dwarf galaxies deviate from a common dwarf spheroidals, showing a DM mass of order 10^6 solar masses; universality is recovered with a quasi-universal mass profile, Walker et al. 2009; McGaugh et al. 2007 also gets $M_{DM} \sim r^2$; putting in the dwarf spheroidals , so again constant surface density: Walker et al. (2010) finds that dwarfs including M31 dwarfs do not give real universality, but close..; tidal stripping might just do it, but it would have to affect all dwarfs in M31; his final comment is that 'details do matter'... recent paper by Penarrubia on tidal stripping from the disk shows that the M31 dwarfs can be understood.

E. Galaxies

Paolo Salucci, Trieste: Universality properties in galaxies and cored density profiles. Alludes to a paper with D. Sciama many years ago, in which they pointed out that DM is distributed very differently from baryonic matter. Uses inner rotation curves to derive limits on the presence of DM; for the biggest galaxies the rotation curves decline outwards, for the small ones they keep rising; introduces the Universal Rotation Curve URC; talks about M31, Corbelli 2010: all models fit except no DM; finds again, that small galaxies are completely dominated by DM, which big galaxies are dominated only in the outer parts; shows baryonic mass fct, and also halo mass fct; small galaxies have 100 times as much DM as baryonic matter, big galaxies only about ten times; inner part of rotation curve quite different from NFW; Bullock et al. 2001 MN 321, 559; Salucci et al. 2003 AA 409, 53; cusp vs core issue highlights a CDM crisis; quotes Klypin 2010; Gentile et al. 2004; cored halos best fits; DDO 47 good example, how NFW fails to fit in central parts; mentions van Eymeren; surface density in cores of small and big galaxies (elliptical?) always the same; but for stars this is not true, that surface density rises with mass; DM surface density rises; cored density means flat at center; key point is again that for big galaxies the rotation curves decline gently, and for small galaxies they rise gently - rotation curves are not flat.

Gianfranco Gentile, Ghent: Surface densities and dark matter in galaxies, work with G. Gilmore, Salucci et al.: Pizzella et al. 2004; N3198, Begeman et al. 1991; CDM works very well on large scales, but has problems on galaxy scales, see Gentile et al. 2005; again, cored means constant density at center, NFW at center means spike at center, not seen; baryons would make CDM central densities even spikier by adiabatic contraction; de Blok & Bosma 2002; Mashchenko et al. 2006; Governato et al. 2010; no consensus in community about how to use baryons in this problem; de Blok 2010: could it be that there are observational problems? Valenzuela et al. 2007 model of hot gas; Burkert (1995) $\rho = \rho_0 r_c^3/(\{r + r_c\}\{r^2 + r_c^2\})$; Donato, Gentile et al. 2009; plotted central DM surface density all $141\, M_\odot \mathrm{pc}^{-2}$ from dwarf spheroidal to large galaxies; this implies that the central acceleration generated by DM is a universal value of $3.2\, 10^{-9}\, \mathrm{cm/s}^2$; see also Kormendy & Freeman a long time ago; also the surface density of baryons (averaged over central scale) is constant, see GG et al. 2009 Nature; at the core radius of the DM the ratio of DM to baryons is the same everywhere, for every galaxy; at r_0 the gravitational acceleration of both baryons and DM is the same everywhere; see de Vega, Salucci, Sanchez 2010; HdV points out some analogy to BH entropy, as things go with surface; Donato, GG, et al. 2009 ! Norma S. keeps mentioning the Bekenstein bound on the thermodynamics of gravitational systems; r_0 is many kpc, so the mass of DM the correlation refers to is very large, much larger than the mass of the central BH.

Janine Van Eymeren, Manchester/Duisburg-Essen: van Eymeren et al. 2009 AA 505, 1 collaboration with various people, among them Dettmar (Bochum); she talks about the core/cusp discrepancy, discusses problems both with observations as with theory; only mergers between cored galaxies give a cored result; problems with simulations (Pedrosa et al. 2009, Navarro et al. 2010); they looked at a sample of dwarf galaxies; HI synthesis observations; tilted ring analysis; quantify non-circular motions; decompose rotation curves into baryons and DM. So they looked at dwarf galaxies: N2366, N4861, N5408, I5152, 2 ESO galaxies; N2366 gives a linear rotation curve in the central region; et al galaxies with lots of detail; they agree with the numbers of Donato et al. (2009), a paper which came out after their paper was accepted; result innermost slope close to zero, always core; 'the measured cores are NOT hidden cusps'; review de Blok 2010.

Chanda J. Jog, Bangalore: Determination of the density profile of DM halos of galaxies: she uses the observed HI distribution; starts with vertical shape of DM halos; in N3741 one can measure the HI disk to 40 stellar disk length scales; Spitzer 1942; Narayan & Jog AA 2002; Banerjee & Jog 2008 ApJ; she finds an oblate halo for M31, with halo axis ratio 0.4; Bailin & Steinmetz 2005, Bett et al. 2007 simulations give a range ob oblateness, 0.4 is at the most

oblate end of what they find; Read et al. 2008: need baryons to simulate galaxies like M31; I bata (2008, unpubl.) confirms the oblateness from stellar stream; Banerjee, Matthews & Jog 2010 New Astron. 15, 89; U7321 isothermal, spherical, high density halo: DM halo dominates all the way from < 1 kpc in this LSB galaxy; best fit requires high gas dispersion, which hinders star formation; Narayan, Saha & Jog 2005 AA; Saha, Levine, Jog & Blitz 2009 ApJ; Jog & Combes 2009 Phys. Rep. Only cores are observed in galaxies (never cusps). She does not find universal DM halo profiles contrary to many astronomical observations and cosmological simulations. This non-universality may be due to the fact that she uses in her fits several free parameters which reproduce non-universal structures. In some galaxies the gas flares in the outer parts without any star formation to drive it.

F. Simulations: Pure DM

Anatoly Klypin, New Mexico SU: LCDM structure, Bolshoi simulation; talks a lot about halo concentration fct; distribution fct of halos above a circular velocity is a power-law, which strongly evolves with time; $n(>V) \sim V^{-3}$: Klypin et al. 2010; satellites follow DM for 0.2 to 2 R_{vir}; Tissera et al. 2009; Gnedin et al. 2004; Duffy et al. 2010; Tinker et al. 2008; Sheth & Tormen ..; Kravtsov et al. 2004; Tasitsiomi et al. 2004; Conroy et al. 2006; Guo et al. 2009; Trujillo-Gomez et al. 2010; Spingob et al. 2007; Pizagno et al. 2007; Geha et al. 2006; luminosity vs circular velocity at 10 kpc: gives correct abundance of halos selected by circular velocity and places them in galaxies with the observed luminosity fct; Stark et al. 2009; Leroy et al. 2008; Williams et al. 2008?9; mass fct of halos at $z \simeq 6 - 10$ too low for reionization models; overabundance of dwarfs with $v_{circ} = 50 km/s$; Tikhonov & Klypin 2008; Conclusion: standard explanation of overabundance of dwarf galaxies does not work: Most are predicted with $V_{circ} = 30 - 50\,\mathrm{km/s}$, observed with $< 20\,\mathrm{km/s}$: Big Problem - he calls himself 'numerical observer'; he seems to get problems between LCDM simulation and observations exactly where WDM gets a free-streaming length.

Andrea Lapi, Rome: Dark matter equilibria in galaxies and galaxy systems: Arguments based on simulations; density perturbation grows, detaches itself from expanding universe, then virializes; then merger tree, see Peebles 1993 e.g.; one finds a NFW profile $\rho \sim r^{-1}(1+r)^{-2}$ with a cutoff; this is scale invariant; so the DM density profile of a galaxy like ours is approximately the same as that of a cluster of galaxies; Halo growth involves first a fast collapse including a few major violent mergers, second a slow accretion with the outskirts evolving from inside out by minor mergers and smooth mass addition; a universal powerlaw correlation $K = \sigma^2 \rho^{-2/3} \sim r^{\alpha}$; by analogy they call it DM entropy; α is 1.25 to 1.3; density profiles are best fitted by Sersic-Einasto models: $\rho \sim r^{-\tau} \exp(-\frac{2-r}{\eta} \times r^{\eta})$; this is also used for stelar mass profiles; see Fillmore & Goldreich 1984, Austin et al. 2005, Lu et al. 2006; Lapi & Cavaliere 2009a; see Bertschinger 1985; e.o.s. of DM is given by the entropy equation $\rho \sigma_r^2 \sim K \rho^{5/3} \sim r^{\alpha} \rho^{5/3}$; see Austin et al. 2005; one can show then that a typical α-profile exists for every $\alpha < 35/27 = 1.296..$; these solutions have an exponential cutoff at large radii, similar to NFW over intermediate radii, and flatter than NFW at small radii; see Lapi & Cavalieri 2009b; see also Hansen & Moore 2006; tested Abell1689; that cluster shows evidence for a higher transition redshift, and a result is a higher concentration; see Kormendy et al. 2009 and Navarro et al. 2010; Prugniel & Simien 1997; summary all from Lapi + ApJ 692, 174, 2009; ApJL 695, L125, 2009; AA 510, 90, 2010; ApJ 698, 580, 2009; ApJ 705, 1019, 2009; AA 2010 in press. Klypin argues that this work is incompatible with simulations, disagreement; key point is use of a modified polytropic e.o.s., the entropy equation.

Rainer Stiele, Uni HD: Cosmological bounds on DM self-interactions: starts again with small scale problem in LSSF; mentions again, that NFW fails in the center relative to data: Salucci et al. 2007; self-interacting DM heats center, also isotropization in central regions: Spergel & Steinhardt 2000 PRL; Dave et al. 2001 ApJ; Yoshida et al. 2000 ApJ; Gnedin & Ostriker 2001: galactic halos have to survive heating from hot cluster halos; Miralda-Escude et al. 2002 ApJ: ellipticity of cluster halos; ever more constraints; Randall et al. 2007 ApJ bullet cluster; Clowe et al. 2006 ApJ; Clowe 2007; all give limits of order $\sigma_{DM}/m_{DM} < 0.1\,\mathrm{cm}^2/\mathrm{g}$; in cosmology period of self-interaction prior to radiation dominated era; scaling arguments lead to WDM; changes the early universe, no effect on MWBG, nucleosynthesis could be affected (better not); BBN then gives a constraint; could change the ^4He content; then $Helium^4$ abundance gives then a constraint on self-interaction: Steigman et al. 2007 ARNPSc upper bound; Hui 2001 PRL 86; applying a similar approach to CDM gives $m_{CDM} < 45$ GeV ruled out if $\sigma > \sigma_{weak}$; then goes into structure formation; possible objects not compact, as pointed out by Andrea Maccio; then Norma S. and HdV say, that in their work there is self-interaction at a level 5 orders of magnitude below the present upper limits.

1. *DM with stars and gas. keV scale DM.*

Yehuda Hoffman, Hebrew U, Jerusalem, hoffman@huji.ac.il: Dark matter halos, with and without baryons: work with Isaac Rodriguez (Hebrew Univ.; his student), Emilio Romano-Diaz (these three one collaboration), Isaac Shlos-

man (Kentucky), Clayton Heller (Statesboro, GA, USA), Stefan Gottloeber (Potsdam), Gustavo Yepes (Madrid), Luis Martinez-Vaquero, Alexander Knebe, Steffen Knollmann. Last 5 CLUES collaboration, from Gottloeber. Two different kinds of halos, with his two different collaborations. The structure of DM halos is well known, but hardly understood analytically; no consensus on baryonic DM halos, no numerical convergence, no consensus on subgrid processes, results depend on implementation of subgrid processes; quotes the Blumenthal, Faber, Flores, Primack 1986 paper ApJ; $\{M_{DM}(r) + M_b(r)\} \times r$ adiabatic constant; Gnedin, Kravtsov, Klypin et al. 2004 ApJ; baryons pull DM into the center by cooling; al + Shlosman, Hoffman 2001 ApJ and 2004 (second paper with J. Primack and F. Combes); dynamical friction transfers energy from one component to the other component; clumps need to be baryon rich; dynamical friction using Chandrasekhar 1943 formula; Anatoly Klypin calls him analytical simulator; Romano-Diaz, Shlosman, Heller, Hoffman (2008 - 2010); feedback from stellar winds and SNe, delayed cooling; very interesting phase space plots, for DM and baryons; shows some interesting plots of the evolution of a DM clump, stars and gas - I am a bit skeptical; at redshift z = 0 the baryons dominate at the center, but the DM density also enhanced at center compared to the non-baryon case; almost isothermal; Adiabatic contraction works, at all times the BDM (DM including the effects of baryons) density exceeds the PDM (pure DM excluding the effects of baryons); the excess of DM at center decreases with time; the dissipative gas makes the DM substructure more resilient against tidal forces, but the central galaxy potential gets deeper, so tidal forces increase; compared with the PDM the BDM subhalos die younger, lose more of their mass, lose more of their orbital energy, population is depleted faster; subhalo mass fct $M_{DM}^{-0.9}$; difference in central flattening between his Romano-Diaz et al collaboration, and Gottloeber et al collaboration; his plots are largely illegible; phase space density plots as fct(r) for DM only: gives radial powerlaw; in BDM case slightly shallower than in PDM case; possible contradiction between codes; dynamical friction time scale over dynamical time is scale free for subhalos; in massive halos ($> 10^{12}\,M_{\odot}$) dynamical friction by subhalos flattens the central DM density cusp, in less massive halos does not flatten the inner density cusp (see also work by al + Ostriker 2009); conjecture that in more massive hosts the dynamical friction brings in more massive baryonic substructures, that puff up the central DM distribution; Paolo S. says, that M33 has a core in DM (no BH).

Andrea Maccio, MPIA, HD: Dark matter at small scales, work with H.W. Rix et al.; will talk about LF of small satellites, from SDSS; Gnedin et al. 2000 on reionization; started with N-body simulations, built merger tree; include tidal stripping, SFR, SN feedback, orbital evolution $->$ LF etc; Somerville et al. 2008, Kang et al. 2005, 2008, Morgana, Monaco et al. 2006, Gnedin 2000, Okamoto et al 2008; Maccio, Kang & Moore 2009, Maccio et al. 2010; Klypin et al. 1999; both SN feedback and reionization are able to change the LF; he claims to use the entire HRD for stellar evolution and mass loss; argues about reionization redshift, uses relatively small numbers like 7.5 to 11; for given DM mass a huge range of stellar mass; he can reproduce the Strigari et al. 2008 plot using CDM; quotes Maccio et al. 2008; Maccio & Fontanot 2010, MN Lett; using WDM models for substructure give $m_{DM} > 1$ keV; he argues that Lyman-alpha and QSO lensing give $m_{DM} > 4$ keV; he uses a thermal relic, while we already know that the relics have to be subthermal...; WDM also reproduces the Strigari et al. plot; he concludes that 3/4 of all satellite galaxies are dark, have only DM; heating of stellar streams (Oderkirchen et al. 2009); streams get substructure from dynamical friction with dark halos: the data look like they are disrupted occasionally, possibly proving the existence of dark halos; his small galaxies are too red; his final conclusion is that he cannot decide with respect to CDM vs WDM; from his point of view both are possible; big argument with Anatoly Klypin on small galaxies; Paolo Salucci tells that he and his team looked for satellites of large spiral galaxies, and detected 1/3 the predicted number; Yehuda Hoffman says that our Galaxy is embedded in two small filaments of the galaxy distribution towards Virgo.

Gustavo Yepes, Madrid: How warm can dark matter be? Constraining the the mass of DM particles from the local universe: Collaboration CLUES 'Constrained Local UniversE Simulation project': determine local flow field, extrapolate back, then use as initial conditions, and work forward again; since the nonlinear evolution strong, you learn conditions; they usually get complexes like Virgo and Fornax, but get a realistic local group 4 - 6 times out of 200 realizations; Hoffman et al. 2008 MN, Martinez-Vaquero et al. 0905.3134, Tikhonov et al. 2009 MN, Zavala et al., 2009 ApJ; says, that M31 has a linear orbit relative to our Galaxy; used then simulation to see, whether the radial orbit assumption gives reasonable masses (a la Kahn & Woltjer 1959): this gives a typical factor 2 to 1/2; Tully-Fischer relation seems to work; efficient suppression of star formation by UV photoionization (Hoeft et al. 2006); substructure LF Metz 2007, Koposov 2008; Tikhonov & Klypin 2008; Tikhonov et al. 2009; study WDM simulations; in WDM models the density in the voids is slightly smaller than in corresponding CDM simulations; problem is with discreteness of numerical fluid at small scales; Wang & White 2007; density profiles almost the same for CDM, 1 keV WDM, and 3 keV WDM (Martinez-Vaquero 2010 PhD Univ. Aut. Madrid); did not use initial random velocities, so no core (central density flat); voids in local Universe, Tikhonov et al. 2009 MN: in WDM the void statistics work better, finding small galaxies; HI velocity function better fitted by WDM than by CDM models; their analysis points towards 1 - 3 keV mass of the DM particle, depending on exact question; some arguments on various codes.

G. DM with stars, gas, magnetic fields and cosmic rays

We know and approximately understand due to Parker, that gas on one side and magnetic fields and cosmic rays on the other side are in pressure equilibrium in a Galactic disk. Similar constraints must govern the ISM in all galaxies, whether small or large. Cosmic rays can heat, but also wander around by diffusion and convection, can undergo adiabatic losses, but also gain energy from compression in shocks. Magnetic fields are probably initially produced by rotating stars in a combination of the battery and dynamo effects, injected into the ISM by stellar winds and supernova explosions, but then brought to full effect by a cosmic ray driven dynamo. The combined action of supernova explosions and cosmic rays then also drives a galactic wind. Clearly a full understanding of the interplay of gas and star formation requires the incorporation of the key physical elements of magnetic fields and cosmic rays.

H. The Bullet Cluster & ΛCDM.

Jounghun Lee, Seoul NU: Bullet cluster is a challenge to LDCM! 1003.0939 (ApJ in press). Bullet cluster one cluster 1.5 peta-$M_{\odot}$, the other 1/10 of that; transverse velocity almost 5000 km/s; probability of finding a bullet like cluster of 0.2 percent level (Hayashi & White 2006); Farrar & Rosen (2007) improved the likelihood by using better data, then likelihood 10^{-7}; so bullet cluster quite unusual in LDCM; Springel & Farrar (2007); therefore bullet cluster not so rare in LDCM, likelihood 0.07 (7 percent); – ; Mastropietro & Burkert 2008: Her work has been to redetermine the likelihood, Crocce et al. 2010: MICE simulation; search for clusters of clusters with bullet like properties in simulation; probability then $10^{-10.5}$, at redshift $z = 0.5$ probability $10^{-8.5}$; he conclusion is: bullet cluster is incompatible with LCDM; Komatsu et al. 2001; Bradac et al. 2008 - other candidates to be similar to bullet cluster.

I. Theory: Phase space and surface gravity constraints

Hector de Vega, Paris: Galaxy properties from linear primordial fluctuations and keV dark matter from theory and observations. HdV talks about phase space redshift dependence; $Q = \rho/\sigma^3$ decreases by Z: he estimates Z of order 40,000, simulations give less; in the estimates he uses $1 < Z < 10,000$; allowing subthermal character gives slightly higher mass; Boyanovsky et al. PRD 77, 043.., 2008, deVega & Sanchez 2010 MN ; everything depends on the phase space density from dwarf galaxies from Gerry Gilmore 2007 and 2008; HdV says, that his result is independent to within a large factor of what the real phase space density is today, involves only the 1/4-power of the phase space density factor Z; HdV argues that this is independent of the cusp/core dispute; HdV uses the spatial average of the Q value, so it does not depend on structural details; shows primordial power spectrum today; for scales smaller than 100 kpc are cut off for keV particles, for larger scales the same as CDM; quotes universal properties like surface density, DM density profile, M_{BH}/M_{halo}; galaxy variables are related by universal empirical relations: one variable remains free; universal quantities may be attractors in dynamical evolution: $\rho(r) = \rho_0 \, F(r/r_0)$, $F(0) = 1, x = r/r_0$, r_0 core radius; e.g. Burkert $1/[(1 + x)(1 + x^2)]$; central density of galaxies $120 \, M_{\odot} \, \mathrm{pc}^{-2} = (17.6 \, \mathrm{MeV})^3$; for $5 \, \mathrm{kpc} < r_0 < 100 \, \mathrm{kpc}$; compares with entropy arguments of BHs, where of course the corresponding energy is Planck scale; matching observations with formulae gives 2.6 keV (2.64.. for Bose, 2.69.. for Fermi particles); he concludes dark matter particle 1.6 keV $< m_{DM} <$ 2 keV. WIMP mass of order 100 GeV disagree with observations by several orders of magnitude; he calls sterile neutrinos the simplest example; mixing angle 10^{-4}; precise measurement of nucleus recoil in tritium beta decay; summarizes a) phase space density, b) proper galaxy density profiles, c) peculiar velocities in clusters,...; arguments on supersymmetry. I reminded the audience of the advantage of early star formation (PLB & AK 2006 PRL); HdV and Norma S both argue about supersymmetry, both say, that supersymmetry by itself does NOT give a heavy DM particle, you also need another symmetry (R-parity), Norma S says, that supersymmetry should appear at much higher energy scale in the universe; HdV emphasizes that with the two mass scales, right-handed neutrino and left-handed neutrino they just give the right abundance from the mixing angle.

Norma Sanchez, Paris: Galaxy properties, keV scale DM from theory and observations, and the power of linear approximations: 1) DM exists, 2) Astrophysical observations point to existence of DM, 3) no WIMP search successful, 4) Proposals keep coming to make DM disappear, changing the laws of physics... lecture A) the mass of the DM particle, B) Boltzmann-Vlasov eq, C) universal properties of galaxies. Various papers from 2008 through 2010, MNRAS, ApJ, etc, and astro-ph; collaborators Boyanovsky, de Vega, Salucci, ..; central density profiles, cores rather than cusps (at very center density law flat; DM energy density, DM velocity dispersion, DM phase space density together give DM particle mass and decoupling temperature; allowed range for velocity dispersion, range of radial scale, gives phase space density to within a factor of 10; $Q = \rho/\sigma^3$ decreases by nonlinear gravitational interactions (Lynden-Bell, Tremaine, Henon 1986);free-streaming length gives $450 \, M_{\odot} < M_z(1+z)^{-3/2} < 4.5 \, 10^6 \, M_{\odot}$; this length

decreases with increasing mass of the particle 8 kpc for 1 keV, and 2 kpc at several keV; decoupling temperature around 100 GeV; DM annihilation cross-section about $10^{-9}\,\mathrm{GeV}^{-2}$, about 10^5 below other limits; for WIMPs the free streaming length is of order 100 AU; so WIMPS strongly disfavored; she pushes universality, 'the first things to understand'; constant central surface density $120\,M_{\odot}\,\mathrm{pc}^{-2}$ over core radius 5 to 100 kpc: Gentile et al. 2009, Donato et al. 2009; gets at the end a universal density profile for galaxies, with just the length scale as parameter; radial scaling Walker et al. 2009 (observations), Vass et al. 2009 (simulations); she says that the agreement between linear theory and observations is remarkable; she gives a range for the DM particle of 1.6 keV $< m_{DM} <$ 2 keV; reminds of the review de Blok 2010; Hoffman et al. 2007; Avila-Reese et al. 2000, Goetz & Sommer-Larsen 2002; Tikhonov et al. 2009; Kashlinsky et al. 2008; Watkins et al. 2009; Lee & Komatsu 2010; Ryan Joung et al. 2009, Holz & Perlmutter 2010; Blasi, Serpico 2009 (pulsar wind nebulae); Maccio wonders why heavy particles give different velocities in entire galaxy situations, asking about Lee & Komatsu 2010; Norma quotes Boyanovsky, HdV & Norma Sanchez 2004 and say, that they generalize Gunn & Tremaine bound, a paper much earlier; so step by step evolution Gunn et al., Hogan et al., now Boyanovsky et al.. Paolo S then says, that he can compute phase space evolution; Norma Sanchez mentions the issue whether baryons could also solve all the short scale problems using wimps - and argues that this will not be possible; argues that universal quantities cannot be changed by a small fraction of baryons; but acknowledges that the simulations have not all been done yet; now Maccio argues that his calculations can account for substructure using wimps and baryons - the point is that in his approach many small units are invisible; N Sanchez argues that this implies many different recipes to solve the different problems, she prefers a unique framework not different recipes and by Occam's razor keV particles are a simpler solution. One would really need keV DM simulations with baryons.

J. Black holes, pulsar kick

The transformation of a left-handed active neutrino into a right-handed sterile neutrino can give a pulsar a kick (Kusenko 2004 IJMPD), possibly explaining all the high linear velocities found for a fraction of all pulsars.

K. Decisive Observations to find the DM particle

1. Very high precision experiments?

Basically all extremely high precision experiments have the chance to discover basic physics: examples are experiments done by Quack (Quack et al. Ann. Rev. Phys. Chem vol. 59, 2008) , Hänsch (Science 319, 1808, 2008) , Marcaide & Irwin Shapiro (IAU Sympos. 110, p.361, 1984).

The first is molecular spectroscopy, the second one uses frequency combs, and the third one micro-arcsecond angular precision astrometry across the universe.

These experimental methods may lead to discover the keV scale DM particle.

2. X-ray emission line

In the case of a right-handed sterile neutrino there should be a weak decay line at a photon energy of just half the mass (e.g. Loewenstein et al. 2009 ApJ; Boyarsky et al. arXiv:1001.0644). This would be proof, if detected with the right spatial profile.

3. Very early star formation

The perhaps most exciting prediction from the concept that DM is a keV right handed sterile neutrino is that massive star formation, black hole formation, and perhaps even supermassive black hole formation start in the redshift range 50 to 1000 (Biermann & Kusenko 2006 PRL).

L. Heavy dark matter particle decay?

From particle physics Supersymmetry suggests with an elegant argument that there should be a lightest supersymmetric particle, which is a dark matter candidate, possibly visible via decay in odd properties of energetic particles and photons:

Gabrijela Zaharijas, Gif-sur-Yvette: DM constraints from Fermi-LAT diffuse observations: on behalf of the Fermi collaboration; launched exactly 2 years ago, June 11, 2008; she uses the LambdaCDM model with WIMPs; the decay of these postulated WIMPs then gives gamma rays; Bergstrom et al. 2009 PRL gives E^{-3} CR-e spectrum; Gustafsson et al. PRL 2007; Abdo et al. 2010 PRL diffuse signal; considers enhancement of diffuse flux due to formation of gravitational structures: extrapolation to below the spatial resolution of the simulation, Bullock et al. 2001, Zavala et al. MN 405, 593 (?); Ullio et al. PRD 2002; Eke et al. 2001 ApJ; Abdo et al. JCAP 2010; Primack, Gilmore, Somerville 0811.3230; Gilmore et al. 2009, 0905.1144; Stecker et al. 0510449; star forming galaxies could make up most of the extragalactic signal, AGN only < 30 percent; Fields et al. 1003.3647; as with increased sensitivity more and more point sources are resolved, the diffuse background goes down, and gets more constraining; comment from the audience, that EGRET saw a much higher diffuse flux, and then it was also claimed that AGN could account for 30 percent: response was that now we have better data on AGN, and their flux distribution;

Observations have discovered i) an upturn in the CR-positron fraction (Pamela: Adriani et al. 2009 Nature), ii) an upturn in the CR-electron spectrum (ATIC: Chang et al. 2008 Nature; Fermi: Aharonian et al. 2009 AA), iii) a flat radio emission component near the Galactic Center (WMAP haze: Dobler & Finkbeiner 2008 ApJ), iv) a corresponding IC component in gamma rays (Fermi haze: Dobler et al. 2009 arXiv), v) the 511 keV annihilation line also near the Galactic Center (Integral: Weidenspointner et al. 2008 NewAR), and most recently, vi) an upturn in the CR-spectra of all elements from Helium (CREAM: Ahn et al. 2009 ApJ, 2010 ApJL).

All these features can be quantitatively explained with the action of cosmic rays accelerated in the magnetic winds of very massive stars, when they explode (Biermann et al. 2009 PRL, 2010 ApJL), based on well-defined predictions from 1993 (Biermann 1993 AA, Biermann & Cassinelli 1993 AA, Biermann & Strom 1993 AA, Stanev et al 1993 AA). While the leptonic part of these observations may be explainable with pulsars and their winds (talk by P. Serpico), the hadronic part clearly needs very massive stars, such as Wolf-Rayet stars, their winds and their explosions. What the cosmic ray work (Biermann et al., from 1993 through 2010) shows, that allowing for the magnetic field topology of Wolf Rayet star winds (see, e.g. Parker 1958 ApJ), both the leptonic and the hadronic part get readily and quantitatively explained, so by Occam's razor the Wolf-Rayet star wind proposal is much simpler.

Pasquale Serpico, CERN: Pamela/Fermi CR lepton data... he mentions pulsar wind nebulae, SNRs; Nature 458, 607, 2009; basically follows the Strong & Moskalenko line; PRL 102, 181101 (2009); 0909.4548 Di Bernardo et al.; Fermi LAT PRL 103, 251101 (2009); Stawarz et al. 0908.1904; D. Grasso et al. 0905.0636; Shaviv et al. PRL 103, 111302 (2009); Kobayashi et al. ApJ 601, 340 (2004); uses a lot of standard arguments; talks a lot about pulsar power; rotational energy of pulsars about two orders of magnitude larger than need to explain Pamela excess; question how to covert a large fraction of Poynting flux into nonthermal particles without any visible thermal flux; Amato & Arons ApJ 653, 325 (2006); Hoshino & Arons Phys of Fluids B 3, 818 (1991); he pushes pulsar wind nebulae as a source for extra CR-positrons and extra CR-electrons. In questioning he argues that with WR-star model you need special parameters, just as with pulsar wind model; I suggested that the polar cap component has now been confirmed through the fit to the CREAM data; then he separated hadronic from leptonic CR data.

In summary there are convincing arguments, that all these observations of cosmic ray positrons and the like are due to normal astrophysical processes, and do not require a special heavy particle to decay.

M. Conclusion

A right-handed sterile neutrino is a candidate to be this DM particle (e.g. Kusenko & Segre 1997 PLB; Fuller et al. 2003 PRD; Kusenko 2004 IJMP; for a review see Kusenko 2009 PhysRep; Biermann & Kusenko 2006 PRL; Stasielak et al. 2007 ApJ; Loewenstein et al. 2009 ApJ): This particle has the advantage to allow star formation very early, near redshift 80, and so also allows the formation of supermassive black holes, possibly formed out of agglomerating massive stars. Black holes in turn also merge, but in this manner start their mergers at masses of a few million solar masses. This readily explains the supermassive black hole mass function. The corresponding gravitational waves are not constrained by any existing limit, and could have given a substantial energy contribution at high redshift.

Our conclusion is that a right-handed sterile neutrino of a mass of a few keV is the most interesting candidate to constitute dark matter.

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FIG. 13: The Meudon Château